



MIT  
International Center for  
Air Transportation

## **SYSTEMS-LEVEL ANALYSIS OF ON DEMAND MOBILITY FOR AVIATION**

Parker D. Vascik and R. John Hansman

*This report is based on the Master's Thesis of Parker D. Vascik submitted to the Department of Aeronautics and Astronautics and the Institute for Data, Systems, and Society on January 27, 2017 in partial fulfillment of the requirements for the degrees of:*

*Master of Science in Aeronautics and Astronautics  
Master of Science in Technology and Policy*

Report No. ICAT-2017-02  
February 2017

MIT International Center for Air Transportation (ICAT)  
Department of Aeronautics & Astronautics  
Massachusetts Institute of Technology  
Cambridge, MA 02139 USA

*[Page Intentionally Left Blank]*

# **Systems-Level Analysis of On Demand Mobility for Aviation**

by

Parker D. Vascik and Prof. R. John Hansman

## **Abstract**

On Demand Mobility (ODM) is an emerging transportation concept that leverages pervasive telecommunication connectivity to enable the real-time matching of consumers with transportation service providers. Having experienced rapid adoption in ground transportation markets, numerous entities are now investigating opportunities to provide aircraft-based ODM within metropolitan areas. Previous research efforts have focused primarily on the technical capabilities of novel electric propulsion aircraft and sought to characterize the market potential for these vehicles.

This thesis complements these initial efforts by adopting a broad view of anticipated aircraft-based ODM services to identify operational constraints and evaluate near and far-term mitigation opportunities. A systems-level analysis was used to capture interdisciplinary influence factors such as limitations placed on ODM networks as a result of air traffic control, ground infrastructure integration, network load balancing, unmanned aircraft interaction and community noise, among others. The holistic considerations of this analysis extend beyond the traditional conceptual design disciplines of engineering and business to include evaluative perspective from the legal, policy, urban planning and sustainability domains.

The first order, systems-level analysis approach for early-phase conceptual design developed in this thesis was applied to a case study in Los Angeles. Promising markets were identified based upon current commuting and wealth patterns. A notional concept of operations was then applied to twelve reference missions within these markets. Scrutiny of these missions revealed a variety of operational challenges from which five preeminent constraints were derived. These constraints may limit or prohibit ODM aircraft operations and include ground infrastructure availability, aircraft noise emissions and air traffic control scalability. Furthermore, significant legal and policy challenges were identified related to low altitude flight, environmental impacts and community acceptance. Findings from this thesis may support the ODM community to develop a system architecting plan that directs technology investments, stakeholder negotiations and network implementation so as to overcome the identified constraints and avoid or internalize negative externalities.

## **Acknowledgements**

This material is based upon work supported by the National Aeronautics and Space Administration under grant number NNX14AT14H issued through the NASA Education Aeronautics Scholarship Program, as well as contract NNL16AA58T. Opinions, interpretations, conclusions and recommendations are those of the authors and not necessarily endorsed by the United States Government.

# Table of Contents

|  |           |
|--|-----------|
| <b>ABSTRACT</b> .....  | <b>3</b>  |
| <b>ACKNOWLEDGEMENTS</b> .....  | <b>4</b>  |
| <b>TABLE OF CONTENTS</b> .....   | <b>5</b>  |
| <b>LIST OF FIGURES</b> .....   | <b>9</b>  |
| <b>LIST OF TABLES</b> .....  | <b>12</b> |
| <b>1 INTRODUCTION</b> .....  | <b>15</b> |
| 1.1 MOTIVATION.....  | 15        |
| 1.2 METHODOLOGICAL GAP .....   | 16        |
| 1.3 SCOPE .....  | 18        |
| 1.4 RESEARCH QUESTIONS .....   | 18        |
| 1.5 METHODOLOGY .....  | 19        |
| 1.6 THESIS OVERVIEW AND ORGANIZATION .....   | 21        |
| <b>2 BACKGROUND AND LITERATURE REVIEW</b> .....  | <b>23</b> |
| 2.1 HISTORICAL UNDERPINNINGS OF ON DEMAND MOBILITY FOR AVIATION .....                              | 23        |
| 2.1.1 <i>The Early Years of Air Transportation</i> .....   | 23        |
| 2.1.2 <i>Urban Air Transportation of the 1960's and 70's</i> .....                                 | 24        |
| 2.1.3 <i>Helicopter Charter Flight Networks</i> .....  | 27        |
| 2.1.4 <i>Inter-City and Commuter Airline Regional Flight Networks</i> .....                        | 28        |
| 2.1.5 <i>Personal Air Transportation</i> .....   | 30        |
| 2.1.6 <i>Concept Revitalization as ODM Aviation</i> .....  | 31        |
| 2.2 ON DEMAND MOBILITY AND AVIATION.....   | 32        |
| 2.2.1 <i>Ground-Based On Demand Mobility</i> .....   | 33        |
| 2.2.2 <i>Air-Based On Demand Mobility</i> .....  | 35        |
| 2.2.3 <i>A Preponderance of Terms</i> .....  | 38        |
| 2.2.3.1 <i>Terminology for Aircraft-Based Transportation in Metropolitan Areas</i> .....           | 38        |
| 2.2.3.2 <i>A Hierarchy of Transportation Modes</i> .....   | 39        |
| 2.3 ENABLING TECHNOLOGIES FOR ODM AVIATION .....   | 40        |
| 2.3.1 <i>Electric Aircraft Performance Overview</i> .....  | 41        |
| 2.3.1.1 <i>First Order Aircraft Performance Model</i> .....  | 42        |
| 2.3.1.2 <i>Comparison of Electric and Conventional Aircraft Performance</i> .....                  | 42        |
| 2.3.1.3 <i>Comparative CO<sub>2</sub> Lifecycle Assessment of Full-Electric ODM Aircraft</i> ..... | 48        |
| 2.3.1.4 <i>Discussion of Electric and Conventional Aircraft Operating Economics</i> .....          | 52        |
| 2.3.2 <i>Telecommunications for ODM Aviation Overview</i> .....                                    | 55        |
| 2.3.3 <i>Autonomy in Aviation Overview</i> .....   | 56        |
| 2.4 MARKET OPPORTUNITY AND CURRENT STATUS OF ODM AVIATION .....                                    | 57        |
| 2.5 SYSTEMS APPROACHES TO INITIAL REQUIREMENTS DEFINITION .....                                    | 61        |
| 2.6 CONSIDERATION OF EXTERNALITIES DURING CONCEPTUAL DESIGN .....                                  | 64        |
| 2.6.1 <i>Externalities Related to Social Equity</i> .....  | 65        |
| 2.6.2 <i>Externalities Related to Environmental Justice</i> .....                                  | 66        |

|          |   |            |
|----------|---|------------|
| <b>3</b> | <b>ODM AVIATION MARKET OPPORTUNITIES AND CASE STUDY DEFINITION</b>                  | <b>71</b>  |
| 3.1      | PROMISING MISSION AND BUSINESS CONCEPTS FOR ODM AVIATION.....                       | 72         |
| 3.2      | L.A. CASE STUDY SYSTEM BOUNDARY IDENTIFICATION .....                                | 74         |
| 3.3      | L.A. CONSUMER DEMAND ESTIMATION AND GEOGRAPHIC LOCATING .....                       | 79         |
| 3.3.1    | <i>Consumer Demand for Helicopter Charter Flights.....</i>                          | 82         |
| 3.3.2    | <i>Consumer Demand for ODM Aviation to Replace Long Commutes .....</i>              | 86         |
| 3.3.3    | <i>Consumer Demand for ODM Aviation from Wealthy Commuters .....</i>                | 89         |
| 3.4      | POTENTIAL ENHANCEMENTS TO CITY STRUCTURE ENABLED BY ODM AVIATION .....              | 91         |
| 3.4.1    | <i>Increase Mobility to Communities Underserved by Surface Transportation .....</i> | 95         |
| 3.4.2    | <i>Foster Regional Urbanization .....</i>   | 96         |
| 3.4.3    | <i>Co-Location of Ground Infrastructure with Consumers' Communities .....</i>       | 97         |
| 3.5      | OPPORTUNITIES TO INCREASE TRANSPORTATION RESILIENCY AND AFFORDABILITY ....          | 97         |
| 3.6      | ODM AVIATION INFLUENCE ON CAREERS IN TRANSPORTATION SERVICES.....                   | 98         |
| 3.7      | OPPORTUNITIES TO REDUCE THE ENVIRONMENTAL IMPACT OF TRANSPORTATION .....            | 99         |
| <b>4</b> | <b>LOS ANGELES CASE STUDY REFERENCE MISSION DEFINITION .....</b>                    | <b>105</b> |
| 4.1      | REFERENCE MISSION DEFINITION APPROACH.....  | 106        |
| 4.2      | DAILY COMMUTE REFERENCE MISSIONS.....   | 108        |
| 4.2.1    | <i>Malibu to Century City Reference Mission.....</i>                                | 108        |
| 4.2.2    | <i>San Bernardino to Glendale City Center Reference Mission .....</i>               | 111        |
| 4.2.3    | <i>Antelope Valley to Los Angeles City Center Reference Mission .....</i>           | 112        |
| 4.3      | NON-COMMUTE POINT TO POINT REFERENCE MISSIONS .....                                 | 113        |
| 4.3.1    | <i>San Diego City Center to Los Angeles City Center Reference Mission .....</i>     | 115        |
| 4.3.2    | <i>Los Angeles City Center to Long Beach Reference Mission.....</i>                 | 116        |
| 4.3.3    | <i>The Beverly Hills Hotel to Los Angeles Airport Reference Mission.....</i>        | 117        |
| 4.3.4    | <i>Redondo Beach to Dodger Stadium Reference Mission .....</i>                      | 118        |
| 4.3.5    | <i>Rancho Palos Verdes to Torrance Memorial Hospital Reference Mission.....</i>     | 119        |
| 4.3.6    | <i>San Marino to Palm Springs Reference Mission .....</i>                           | 120        |
| 4.4      | RANDOMLY SELECTED REFERENCE MISSIONS .....  | 120        |
| 4.4.1    | <i>Randomly Selected Reference Mission 1: San Bernardino to Perris .....</i>        | 121        |
| 4.4.2    | <i>Randomly Selected Reference Mission 2: Arleta to Corona.....</i>                 | 122        |
| 4.4.3    | <i>Randomly Selected Reference Mission 3: Altadena to Culver City.....</i>          | 122        |
| 4.5      | L.A. CASE STUDY REFERENCE MISSION DEFINITION SUMMARY .....                          | 123        |
| <b>5</b> | <b>ODM AVIATION OPERATIONAL CONSTRAINTS IDENTIFICATION .....</b>                    | <b>127</b> |
| 5.1      | NEAR-TERM ODM AVIATION NOTIONAL CONOPS DEFINITION .....                             | 127        |
| 5.2      | REFERENCE MISSION OPERATIONAL CHALLENGES IDENTIFICATION .....                       | 129        |
| 5.2.1    | <i>ConOps Step 1: Customer Submits a Travel Request.....</i>                        | 129        |
| 5.2.2    | <i>ConOps Step 2: Aircraft Routed to the Nearest TOLA.....</i>                      | 129        |
| 5.2.3    | <i>ConOps Step 3: Ground Transportation from the Origin to the TOLA.....</i>        | 132        |
| 5.2.4    | <i>ConOps Step 4: Customer Arrives the TOLA and is Prepared for Takeoff.....</i>    | 132        |
| 5.2.5    | <i>ConOps Step 5: Flight Segment.....</i>   | 133        |
| 5.2.5.1  | <i>Malibu to Century City Airspace Considerations .....</i>                         | 133        |
| 5.2.5.2  | <i>Air Traffic Interaction.....</i>   | 135        |
| 5.2.5.3  | <i>Ground Population Noise Exposure.....</i>  | 137        |

|          |   |            |
|----------|---|------------|
| 5.2.5.4  | Mission Flight Profile Development.....   | 137        |
| 5.2.5.5  | Potential ODM Challenges from the Flight Segment.....   | 141        |
| 5.2.6    | <i>ConOps Step 6: Aircraft Arrives at Destination and Customer Disembarks</i> .....                                 | 142        |
| 5.2.7    | <i>ConOps Step 7: Customer Takes Ground Transportation to Final Destination</i> ....                                | 142        |
| 5.2.8    | <i>ConOps Step 8: Aircraft Recharges Batteries</i> .....  | 142        |
| 5.2.9    | <i>Network Impacts of Mission ConOps</i> .....  | 143        |
| 5.3      | OPERATIONAL CHALLENGES RESULTING FROM NEGATIVE EXTERNALITIES.....   | 145        |
| 5.3.1    | <i>ODM Aviation Enabled Socio-Economic Segregation</i> .....  | 146        |
| 5.3.2    | <i>Displaced Ridership and Funding for Surface Transportation Modes</i> .....                                       | 148        |
| 5.4      | POTENTIAL CHALLENGES FOR ODM AVIATION.....  | 148        |
| 5.5      | ODM AVIATION CONSTRAINTS AND ISSUES .....   | 150        |
| 5.5.1    | <i>ODM Aviation Constraints</i> .....   | 150        |
| 5.5.2    | <i>ODM Aviation Issues</i> .....  | 151        |
| 5.6      | CONSTRAINT SENSITIVITY TO ODM AVIATION NETWORK SCALE.....   | 151        |
| <b>6</b> | <b>LEGAL AND REGULATORY CONSIDERATIONS FOR LOW ALTITUDE</b>   |            |
|          | <b>AIRCRAFT OPERATIONS .....</b>  | <b>153</b> |
| 6.1      | INTRODUCTION .....  | 154        |
| 6.2      | THE STATUS QUO OF AVIATION IN THE UNITED STATES.....  | 156        |
| 6.2.1    | <i>Operating Altitude Minimums</i> .....  | 157        |
| 6.2.2    | <i>Approaches to Aircraft Separation</i> .....  | 158        |
| 6.2.3    | <i>Takeoff and Landing Operations</i> .....   | 159        |
| 6.2.4    | <i>Acceptance and Historical Challenges to the Status Quo Aviation System</i> .....                                 | 160        |
| 6.2.5    | <i>Impending Challenges to the Status Quo Aviation System</i> .....   | 160        |
| 6.3      | POLICY AND LEGAL UNCERTAINTIES CONCERNING LOW ALTITUDE AVIATION .....   | 161        |
| 6.3.1    | <i>Who Has Ownership and Regulative Authority of Low Altitude Airspace?</i> .....                                   | 162        |
| 6.3.2    | <i>How are Landowners' Rights Balanced with a Citizen's Right to Flight and Use of the National Airspace?</i> ..... | 169        |
| 6.3.2.1  | Trespass.....   | 170        |
| 6.3.2.2  | Nuisance.....   | 170        |
| 6.3.2.3  | Voyeurism.....  | 171        |
| 6.3.2.4  | Invasion of Privacy .....   | 171        |
| 6.4      | IMPACT OF POLICY AND LEGAL UNCERTAINTIES ON UAS AND ODM AVIATION .....  | 172        |
| 6.4.1    | <i>Potential Limitations on Operations below Historical "Navigable Airspace"</i> .....                              | 173        |
| 6.4.1.1  | FAA as the Sole Aircraft Operations Regulator .....   | 173        |
| 6.4.1.2  | State or Local Municipalities Obtain Regulatory Control of Operations below Navigable Airspace.....                 | 173        |
| 6.4.1.3  | Assignment of Significant Low Altitude Airspace Rights to Landowners.....   | 174        |
| 6.4.2    | <i>Potential Limitation on Operations in Historical "Navigable Airspace"</i> .....                                  | 175        |
| 6.5      | POTENTIAL APPROACHES TO RESOLVE POLICY AND LEGAL UNCERTAINTIES.....   | 176        |
| 6.5.1    | <i>Airspace Regulation</i> .....  | 176        |
| 6.5.2    | <i>Airspace Ownership and Protection of Landowner Rights</i> .....  | 178        |
| 6.5.2.1  | Private Airspace Ownership Demarcation Altitude.....  | 178        |
| 6.5.2.2  | A "Continuum of Acceptability" for Low Altitude Aircraft Operations.....  | 179        |
| 6.5.2.3  | Avigation Easements as a Mechanism to Protect the Rights of Landowners and Aircraft Operators .....                 | 180        |
| 6.5.3    | <i>Airspace Design and Air Traffic Management</i> .....   | 181        |

|          |   |            |
|----------|---|------------|
| 6.6      | SUMMARY .....   | 183        |
| <b>7</b> | <b>REVIEW OF OPERATIONAL CONSTRAINT MITIGATION APPROACHES....</b>                     | <b>187</b> |
| 7.1      | AVAILABILITY OF TAKEOFF AND LANDING AREAS .....                                       | 188        |
| 7.1.1    | <i>Existing Aviation Ground Infrastructure</i> .....                                  | 189        |
| 7.1.2    | <i>Approaches to Increase the Availability of ODM Aviation TOLAs</i> .....            | 192        |
| 7.1.3    | <i>Feasibility of Proposed Approaches to Increase the Availability of TOLAs</i> ..... | 197        |
| 7.1.3.1  | Influence of Aircraft Performance Limitations on TOLA Requirements.....               | 198        |
| 7.1.3.2  | Regulatory Influence on TOLA Development .....  | 200        |
| 7.1.3.3  | Community Acceptance Influence on TOLA Development .....                              | 203        |
| 7.1.3.4  | Business Influence on TOLA Development .....  | 204        |
| 7.1.4    | <i>Summary of Mitigation Potential for TOLA Availability</i> .....                    | 204        |
| 7.2      | SCALABILITY OF ODM NETWORKS UNDER AIR TRAFFIC CONTROL .....                           | 204        |
| 7.2.1    | <i>Current Low Altitude ATC Proposals</i> .....                                       | 205        |
| 7.2.2    | <i>Investigation of ATC in Low Altitude Controlled Airspaces</i> .....                | 208        |
| 7.2.2.1  | Review of LAX ASDE-X Flight Trajectory Data .....                                     | 208        |
| 7.2.2.2  | Controlled Airspace Utilization in Los Angeles .....                                  | 211        |
| 7.2.3    | <i>Dynamic, Fine-Scale Airspace Allocation</i> .....                                  | 211        |
| 7.2.4    | <i>Summary of Mitigation Potential to Scale ODM Networks under ATC</i> .....          | 216        |
| 7.3      | AIRCRAFT NOISE.....   | 217        |
| 7.3.1    | <i>Regulatory and Legal Pathways by which Aircraft Noise may Limit Operations</i> ..  | 217        |
| 7.3.2    | <i>Current Approaches to Aviation Noise Mitigation</i> .....                          | 219        |
| 7.3.3    | <i>Potential Noise Mitigation Opportunities for ODM Aviation</i> .....                | 219        |
| 7.4      | COMMUNITY ACCESS TO TAKEOFF AND LANDING AREAS .....                                   | 221        |
| 7.5      | SCALABILITY OF ODM NETWORKS OPERATING OUTSIDE ATC .....                               | 225        |
| <b>8</b> | <b>CONCLUSION .....</b>   | <b>227</b> |
| 8.1      | REVIEW OF THE THESIS RESEARCH QUESTIONS .....   | 227        |
| 8.2      | ADDITIONAL CONTRIBUTIONS .....  | 234        |
| 8.3      | LIMITATIONS OF STUDY AND FUTURE WORK .....  | 236        |
| 8.4      | FINAL THOUGHTS .....  | 239        |
| <b>9</b> | <b>REFERENCES.....</b>  | <b>241</b> |
|          | <b>ACRONYMS AND ABBREVIATIONS.....</b>  | <b>253</b> |
|          | <b>APPENDIX A: REFERENCE MISSION DEFINITIONS .....</b>                                | <b>255</b> |
|          | <b>APPENDIX B: REFERENCE MISSION CONOPS REVIEW .....</b>                              | <b>277</b> |
|          | <b>APPENDIX C: REVIEW OF U.S. AIRSPACE DEFINITIONS .....</b>                          | <b>297</b> |
|          | <b>APPENDIX D: OVERVIEW OF ODM AVIATION EXTERNALITIES AND IMPACTS</b><br><b>.....</b> | <b>300</b> |



## List of Figures

|   |     |
|---|-----|
| Figure 1. Example aircraft proposed for use in ODM for Aviation.....                                      | 15  |
| Figure 2. First principles analysis approach .....  | 20  |
| Figure 3. New York Airways helicopter services .....  | 25  |
| Figure 4. Examples of intermodal ground and aviation infrastructure proposed in 1973 .....                | 26  |
| Figure 5. VTOL commuter service concept .....   | 29  |
| Figure 6. NASA technology development programs for VTOL aircraft 1987-2011 .....                          | 29  |
| Figure 7. Hierarchy of transportation modes and relevant terminology from the literature.....             | 39  |
| Figure 8. Weight trend for single engine propeller-driven aircraft.....                                   | 44  |
| Figure 9. Comparison of energy requirements between full-electric and piston engine aircraft..            | 45  |
| Figure 10. Comparison of full-electric and piston engine aircraft overall efficiency.....                 | 46  |
| Figure 11. Full-electric aircraft weight fractions and energy requirements.....                           | 48  |
| Figure 12. Electricity generation resource mix and CO <sub>2</sub> emissions rate for U.S. states.....    | 50  |
| Figure 13. Comparison of CO <sub>2</sub> emissions for conventionally and electrically powered aircraft . | 52  |
| Figure 14. Direct operating cost breakdown for three Cape Air routes from St-Louis in 2015 ...            | 53  |
| Figure 15. Comparison of energy costs between full-electric and piston engine aircraft.....               | 54  |
| Figure 16. Notional diagram of the “long tail” of the transportation market .....                         | 59  |
| Figure 17. Consumer utilization of aircraft transportation modes.....                                     | 68  |
| Figure 18. Steps one and two of the first principles approach.....  | 71  |
| Figure 19. Relative density of commuter flows in the Southern California megaregion .....                 | 75  |
| Figure 20. Typical helicopter charter service offerings by a representative L.A. company.....             | 77  |
| Figure 21. L.A. basin case study system boundary.....   | 78  |
| Figure 22. Southern California commuter mobility mode cumulative density function (CDF)...                | 81  |
| Figure 23. Southern California commuter mobility mode CDF with ODM Aviation.....                          | 82  |
| Figure 24. Cost per passenger mile versus helicopter charter flight mission range for L.A. ....           | 85  |
| Figure 25. Commuter patterns between the regions of California.....                                       | 87  |
| Figure 26. Common mega commuter routes into Los Angeles County and San Diego County. .                    | 89  |
| Figure 27. Estimated household valuation heat map of the Los Angeles basin .....                          | 90  |
| Figure 28. High income commuter and mega commuter communities within the L.A. basin ....                  | 91  |
| Figure 29. Notional diagram of an idealized “urban star” city structure. ....                             | 92  |
| Figure 30. Concept of how ODM Aviation may influence a city’s mobility coverage.....                      | 94  |
| Figure 31. Nodal ODM Aviation ground infrastructure .....   | 97  |
| Figure 32. Comparison of car and aircraft operations for identical routes in ideal conditions...          | 100 |
| Figure 33. Comparison of private car and ODM aircraft operations with surface congestion...               | 102 |
| Figure 34. Comparison of private car and ODM aircraft for circuitous surface route .....                  | 102 |
| Figure 35. Comparison of operations for an aircraft with a high load factor .....                         | 102 |
| Figure 36. Comparison of car and ODM aircraft operations in noise sensitive communities....               | 103 |
| Figure 37. First principles approach to develop a set of ODM Aviation reference missions.....             | 105 |
| Figure 38. Malibu to Century City reference mission .....   | 109 |
| Figure 39. Malibu to Century City reference mission travel time & average speed .....                     | 110 |
| Figure 40. Malibu inverse laborshed .....   | 111 |
| Figure 41. San Bernardino to Glendale City Center reference mission.....                                  | 112 |
| Figure 42. Antelope Valley to Los Angeles City Center reference mission.....                              | 113 |
| Figure 43. San Diego to Los Angeles City Center reference mission .....                                   | 115 |
| Figure 44. Los Angeles City Center to Long Beach reference mission.....                                   | 116 |
| Figure 45. Beverly Hills Hotel to Los Angeles Airport reference mission .....                             | 117 |

|   |     |
|---|-----|
| Figure 46. Redondo Beach to Dodger Stadium reference mission .....                                  | 118 |
| Figure 47. Rancho Palos Verdes to Torrance Memorial Hospital reference mission.....                 | 119 |
| Figure 48. San Marino to Palm Springs reference mission overview.....                               | 120 |
| Figure 49. San Bernardino to Perris reference mission .....   | 121 |
| Figure 50. Arleta to Corona reference mission.....  | 122 |
| Figure 51. Altadena to Culver City reference mission .....  | 123 |
| Figure 52. Reference mission ConOps evaluation process and evaluation lenses .....                  | 127 |
| Figure 53. Notional aircraft ConOps for an ODM Aviation mission .....                               | 128 |
| Figure 54. Current TOLA infrastructure in Malibu .....  | 130 |
| Figure 55. The nearest available aircraft staging infrastructure to Malibu.....                     | 131 |
| Figure 56. ATC entrance requirements and airspeed limits for flight below 10,000 ft MSL.....        | 134 |
| Figure 57. Class B, C and D airspaces in proximity to Malibu and Century City.....                  | 134 |
| Figure 58. FAA terminal area chart for the Malibu to Century City reference mission.....            | 136 |
| Figure 59. Population density of census block groups surrounding Malibu and Century City ..         | 137 |
| Figure 60. Malibu to Century City flight profile development.....                                   | 138 |
| Figure 61. ODM Aviation ConOps diagram for the Malibu to Century City network .....                 | 144 |
| Figure 62. Dependence of single-pad TOLA throughput on aircraft turn-time.....                      | 145 |
| Figure 63. Geographic distribution of race in the L.A. basin .....                                  | 147 |
| Figure 64. Notional dependency of ODM constraints on network density (scale).....                   | 152 |
| Figure 65. Evaluation lenses to identify challenges from legal and regulatory considerations..      | 153 |
| Figure 66. Airspace structure of the U.S. national airspace system .....                            | 156 |
| Figure 67. Status quo framework for aircraft flight minimums.....                                   | 158 |
| Figure 68. Legal process for the development of aircraft operating regulations .....                | 162 |
| Figure 69. Amazon airspace design proposal for small UAS operations below 500 ft.....               | 182 |
| Figure 70. Google airspace design proposal for small UAS operations below 500 ft.....               | 182 |
| Figure 71. Notional diagram for a continuum of acceptability in low altitude operations .....       | 185 |
| Figure 72. Investigation of mitigation techniques for the identified operational challenges.....    | 188 |
| Figure 73. Geographic location and type of existing aviation ground infrastructure in L.A.....      | 191 |
| Figure 74. Existing heliport infrastructure drops off outside of the central business district..... | 191 |
| Figure 75. TOLA availability new infrastructure development reference area .....                    | 193 |
| Figure 76. Potential TOLA infrastructure options .....  | 194 |
| Figure 77. Potential geographic distribution of TOLAs if co-located with gas stations .....         | 195 |
| Figure 78. Potential geographic distribution of TOLAs if co-located with gas stations .....         | 196 |
| Figure 79. Potential geographic distribution of TOLAs if co-located with 50'x50' spaces.....        | 197 |
| Figure 80. Height-velocity diagram for a Bell 204B helicopter .....                                 | 198 |
| Figure 81. VFR heliport approach/departure and transitional surfaces .....                          | 200 |
| Figure 82. Impact of PUC § 21662.5 regulation.....  | 203 |
| Figure 83. Surface-level controlled airspaces in the L.A. basin .....                               | 207 |
| Figure 84. LAX ASDE-X radar coverage.....   | 208 |
| Figure 85. LAX ASDE-X annual flight density heat map (300 ft to 500 ft) .....                       | 209 |
| Figure 86. LAX ASDE-X annual flight density heat map (700 ft to 900 ft) .....                       | 210 |
| Figure 87. LAX ASDE-X annual flight density heat map (1500 to 1700 ft).....                         | 210 |
| Figure 88. Los Angeles basin airspace utilization by commercial and GA operators.....               | 211 |
| Figure 89. Notional diagram of dynamic, fine-scale airspace allocation .....                        | 213 |
| Figure 90. Notional diagram of dynamic, fine-scale airspace allocation (2).....                     | 213 |
| Figure 91. Current aircraft separation standards for low altitude operations .....                  | 215 |

|  |     |
|--|-----|
| Figure 92. Notional ATM evolution .....  | 216 |
| Figure 93. Regulatory pathways for operational restrictions due to aircraft noise .....        | 218 |
| Figure 94. Concepts to integrate TOLAs with ground transportation infrastructure.....          | 224 |
| Figure 95. Notional ATM evolution .....  | 232 |
| Figure 96. San Bernardino to Glendale reference mission travel time & average speed .....      | 256 |
| Figure 97. San Bernardino origin point inverse laborshed heat map.....                         | 257 |
| Figure 98. Antelope Valley to Los Angeles reference mission travel time & average speed ....   | 259 |
| Figure 99. Antelope Valley origin point inverse laborshed heat map .....                       | 260 |
| Figure 100. San Diego to Los Angeles reference mission travel time & average speed.....        | 262 |
| Figure 101. Los Angeles to Long Beach reference mission travel time & average speed .....      | 264 |
| Figure 102. Beverly Hills Hotel to LAX reference mission travel time & average speed .....     | 266 |
| Figure 103. Redondo Beach to Dodger Stadium ref. mission travel time & average speed .....     | 267 |
| Figure 104. Rancho Palos Verdes to Torrance Mem. Hospital travel time & average speed ....     | 269 |
| Figure 105. San Marino to Palm Springs reference mission travel time & average speed.....      | 271 |
| Figure 106. San Bernardino to Perris reference mission travel time & average speed .....       | 273 |
| Figure 107. Arleta to Corona reference mission travel time & average speed .....               | 274 |
| Figure 108. Altadena to Culver City reference mission travel time & average speed.....         | 276 |
| Figure 109. Current TOLA infrastructure in the San Diego City Center .....                     | 278 |
| Figure 110. San Diego VFR Flyway Planning Chart .....  | 280 |
| Figure 111. Population density of census block groups between San Diego and Los Angeles .      | 282 |
| Figure 112. Potential flight paths from San Diego City Center to Los Angeles City Center ..... | 283 |
| Figure 113. Route planning for San Diego departure towards Los Angeles .....                   | 284 |
| Figure 114. Route planning for Los Angeles arrival from San Diego.....                         | 285 |
| Figure 115. ODM Aviation ConOps diagram for San Diego to Los Angeles .....                     | 290 |
| Figure 116. Current TOLA infrastructure near the Beverly Hills Hotel.....                      | 291 |
| Figure 117. Beverly Hills TOLA on Wilshire Boulevard to LAX heliport route planning.....       | 293 |
| Figure 118. Population density of census block groups between Beverly Hills & LAX .....        | 294 |

## List of Tables

|  |     |
|--|-----|
| Table 1. Current helicopter charter and sightseeing operations in major world cities .....   | 27  |
| Table 2. Potential challenges for ground-based ODM business models in aviation .....   | 36  |
| Table 3. Potential benefits and positive externalities of ODM Aviation in metropolitan regions.  | 37  |
| Table 4. History of terminology for aircraft-based transportation in metropolitan areas .....  | 38  |
| Table 5. Cirrus SR22 specifications.....   | 43  |
| Table 6. Notional full-electric aircraft specifications based on current technology .....  | 44  |
| Table 7. 2014 greenhouse gas emissions for representative U.S. subregions.....   | 50  |
| Table 8. Potential benefits and challenges of autonomous automobiles. ....   | 56  |
| Table 9. Manufacturers proposing to develop and produce ODM aircraft.....  | 60  |
| Table 10. Business concepts for ODM Aviation. ....   | 73  |
| Table 11. Alternative, non-commercial ODM business concepts for novel aircraft. ....   | 73  |
| Table 12. Review of select Southern California helicopter charter companies .....  | 77  |
| Table 13. Comparison of key performance and cost attributes of common mobility modes. ....   | 80  |
| Table 14. Pricing information for select helicopter charter services in the L.A. region.....   | 83  |
| Table 15. Comparison of fare per passenger mile for L.A. region helicopter charter services. ...   | 84  |
| Table 16. Mean travel time and distance for the top 10 U.S. mega commuter flows.....   | 87  |
| Table 17. Most common mega commuter routes in California .....   | 88  |
| Table 18. Operating attributes of aircraft that may influence mobility and city structure.....   | 93  |
| Table 19. Scenarios where ODM aircraft reduce environmental impacts compared to cars.....  | 101 |
| Table 20. Key operating factors that influence the environmental impact of aircraft ops.....   | 103 |
| Table 21. Summary and characteristics of the 12 reference missions .....   | 106 |
| Table 22. Malibu to Century City reference mission specifications.....   | 109 |
| Table 23. Malibu to Century City reference mission ground transportation study .....   | 110 |
| Table 24. Reference missions summary. ....   | 125 |
| Table 25. Notional mission ConOps for ODM Aviation.....  | 128 |
| Table 26. Key characteristics of airspaces near Malibu and Century City .....  | 135 |
| Table 27. Malibu to Century City water route trip analysis .....   | 139 |
| Table 28. Malibu to Century City direct route trip analysis .....  | 139 |
| Table 29. Malibu to Century City increased speed route trip analysis .....   | 140 |
| Table 30. Malibu to Century City flight profile comparisons .....  | 141 |
| Table 31. Malibu to Century City reference mission ConOps duration breakdown .....   | 144 |
| Table 32. Potential ODM Aviation operational challenges .....  | 149 |
| Table 33. ODM Aviation constraints.....  | 150 |
| Table 34. ODM Aviation issues.....   | 151 |
| Table 35. Summary of the first legal & regulatory question relevant to low altitude aviation ..  | 154 |
| Table 36. Summary of the second legal & regulatory question relevant to low alt. aviation.....   | 155 |
| Table 37. Airspace ownership and regulatory authority from current statutes and regulations .  | 165 |
| Table 38. Summary of key court cases concerning low altitude flight and property rights .....  | 168 |
| Table 39. Summary of key court cases concerning low altitude flight and privacy rights.....  | 172 |
| Table 40. Airspace ownership and regulatory authority as derived from current statutes and regulations with potential low altitude airspace ownership demarcation altitudes..... | 184 |
| Table 41. Existing aviation ground infrastructure in the Los Angeles basin.....  | 189 |
| Table 42. Operational challenges for ODM Aviation resulting from low TOLA availability ...   | 190 |
| Table 43. Potential approaches to increase TOLA availability .....   | 192 |
| Table 44. Regulations that potentially create TOLA certification challenges.....   | 201 |

|   |     |
|---|-----|
| Table 45. Regulations that potentially restrict off-TOLA operations.....                          | 202 |
| Table 46. Challenges for the scalability of ATC to support low altitude aircraft operations ..... | 205 |
| Table 47. Proposed approaches to low altitude ATC scalability .....                               | 206 |
| Table 48. Dynamic, fine-scale airspace allocation architecting and implementation questions       | 214 |
| Table 49. DFRA closure event description and characteristics .....                                | 214 |
| Table 50. Aircraft and helicopter operational restrictions due to noise at major L.A. airports..  | 217 |
| Table 51. Technology-based ODM aircraft noise reduction proposals .....                           | 220 |
| Table 52. Noise reduction operations enhanced by potential ODM aircraft capabilities .....        | 221 |
| Table 53. Potential TOLA access and safety infrastructure requirements.....                       | 222 |
| Table 54. ODM Aviation constraints.....   | 228 |
| Table 55. ODM Aviation issues.....  | 229 |
| Table 56. Notional leading indicators analysis for ODM Aviation implementation .....              | 237 |
| Table 57. San Bernardino to Glendale reference mission specifications.....                        | 255 |
| Table 58. San Bernardino to Glendale reference mission ground transportation study .....          | 255 |
| Table 59. Antelope Valley to Los Angeles reference mission specifications.....                    | 257 |
| Table 60. Antelope Valley to Los Angeles reference mission ground transportation study. ....      | 258 |
| Table 61. San Diego to Los Angeles reference mission specifications .....                         | 261 |
| Table 62. San Diego to Los Angeles reference mission ground transportation study .....            | 261 |
| Table 63. Los Angeles to Long Beach reference mission specifications .....                        | 262 |
| Table 64. Los Angeles to Long Beach reference mission ground transportation study .....           | 263 |
| Table 65. Beverly Hills Hotel to Los Angeles Airport reference mission specifications .....       | 264 |
| Table 66. Beverly Hills Hotel to LAX reference mission ground transportation study .....          | 265 |
| Table 67. Redondo Beach to Dodger Stadium reference mission specifications .....                  | 266 |
| Table 68. Redondo Beach to Dodger Stadium reference mission ground transportation study.          | 267 |
| Table 69. Rancho Palos Verdes to Torrance Mem. Hospital reference mission specifications .        | 268 |
| Table 70. Rancho Palos Verdes to Torrance Mem. Hospital ground transportation study. ....         | 269 |
| Table 71. San Marino to Palm Springs reference mission specifications.....                        | 270 |
| Table 72. San Marino to Palm Springs reference mission ground transportation study.....           | 271 |
| Table 73. San Bernardino to Perris reference mission specifications.....                          | 272 |
| Table 74. Malibu to Century City reference mission ground transportation study .....              | 272 |
| Table 75. Arleta to Corona reference mission specifications .....                                 | 273 |
| Table 76. Arleta to Corona reference mission ground transportation study. ....                    | 274 |
| Table 77. Altadena to Culver City reference mission specifications.....                           | 275 |
| Table 78. Altadena to Culver City reference mission ground transportation study.....              | 275 |
| Table 79. San Diego to Los Angeles City Center flight profile comparisons .....                   | 288 |
| Table 80. San Diego to Los Angeles ODM aircraft daily operating activity time shares .....        | 290 |
| Table 81. Charging time requirements as a percentage of the overall mission block time .....      | 296 |
| Table 82. Los Angeles basin case study airspace type and requirements summary .....               | 299 |
| Table 83. Potential environmental justice externalities resulting from ODM Aviation .....         | 300 |
| Table 84. Potential social equity externalities resulting from ODM Aviation .....                 | 301 |

[Intentionally Left Blank]

# 1 Introduction

## 1.1 Motivation

The aerospace industry is currently experiencing the emergence of a potentially disruptive set of related technologies that may open up an entire new sector of aviation and air transportation. First to appear, Unmanned Aircraft Systems (UAS) have proliferated private, commercial and military markets providing fundamentally new capabilities across hundreds of applications. Secondly, On Demand Mobility (ODM) for Aviation is an emerging concept that leverages increased connectivity through smartphones to enable the real-time matching of consumers and service providers for point-to-point transportation with networks of novel vertical takeoff and landing (VTOL) aircraft.

Ground based transportation companies such as Uber and Lyft have set the example for ODM services and provided a proof of concept for the industry; now many entrepreneurs aim to repeat the same business model in air transportation. Proponents of ODM Aviation (as the concept is referred to short-hand in this thesis) propose that recent advancements in electric propulsion, energy storage and automation will make all-electric, VTOL aircraft available and economically viable by 2020 [1], [2]. Figure 1 presents images of three ODM aircraft displaying the wide variety of configurations these vehicles may adopt.



Figure 1. Example aircraft proposed for use in ODM for Aviation.

Perceiving the technology readiness level of the aircraft and information systems necessary for ODM Aviation as relatively mature, and considering lessons learned through the Concorde, Very Light Jet (VLJ) and fractional jet ownership markets, entrepreneurs and investors are now investigating potential operational challenges ODM Aviation may encounter. Responding to this need, an ODM Aviation case study was conducted in this thesis in close association with the NASA Aeronautics Systems Analysis Branch and the greater ODM Aviation community. It was the aim of this research to identify implementation and operational challenges for ODM Aviation, focus the ODM Aviation community on these issues, and support the development of mitigation approaches before the issues became costly set-backs downstream in the development pipeline.

The current mobility options available to Americans have degraded in quality over the past decades providing slower, less available and more expensive transportation than in previous years; this has primarily occurred as a result of increasing congestion and decaying infrastructure. A significant majority of U.S. transportation, especially private citizen mobility, currently relies upon private automobile ownership. Dramatic growth in urban and suburban density has overwhelmed roadway capacity leading to increased congestion. Alternatives to the private car, including many modes of

public transportation by bus and train, are experiencing severe funding challenges resulting in degraded service [3]. Finally, even the convenience of transportation by aircraft has been degraded as security and increased demand cause severe congestion at major airports [4].

Due to these factors, significant market demand exists for a new mode of transportation that reduces (or avoids) congestion and provides individuals with greater mobility. Aircraft-based mobility shows promise to meet these goals by avoiding surface congestion and providing higher speed transportation over longer distances. Recognizing this potential, the concept of On Demand Mobility for Aviation has appeared numerous times over the past century, albeit under the banner of different names such as intracity air transportation, metrotaxis, or personal air transportation. The concept was revisited by industry and society each time a new flight technology emerged that was perceived to overcome the fatal challenges of the previous iteration.

In a bit of symmetry, 47 years before the publication of this thesis the MIT Flight Transportation Laboratory (the precursor to the MIT International Center for Air Transportation) issued a report titled “Concept Studies for Future Intracity Air Transportation Systems” under contract from NASA. Incredibly, this 1970 report identified many of the same fundamental challenges that this thesis proffers ODM Aviation must overcome today. This thesis will discuss this previous report and others, review how new technologies and operational capabilities have overcome some of the critical challenges from earlier iterations of ODM Aviation, and then investigate how the remaining challenges may possibly be addressed.

## ***1.2 Methodological Gap***

The methodological contribution of this thesis also extends well beyond the ODM Aviation community. The burgeoning commercial UAS market and emerging ODM Aviation industry both epitomize “disruptive” technologies and the unique challenges they face for integration into society. Disruptive technologies have generated dramatic structural changes in economics, politics and societal norms in all parts of the world over the past century. Today, familiar machines and systems such as air conditioning, interstate highways, airplanes and smart phones are indispensable enablers of modern life.

With the steady progression of the Information Age, the rate of technological diffusion into society is also accelerating bringing new devices and capabilities to people at ever faster rates. Furthermore, modern communications capabilities are linking together previously stand-alone technologies into large, cooperating interconnected systems. This development, often termed the “internet of things,” stands to bring about “smart” cities and “smart” homes (among other smart networks) where nearly every technology from the climate control down to the toaster are digitally integrated.

While such technological advances promise to improve efficiency and enhance user capabilities, they also present significant new challenges for engineers, innovators, business managers, regulators and operators. Traditionally, new products (such as a car) could more or less be designed subject to a set of business needs (projected markets), relevant regulations (constraints) and technology capabilities, without explicit consideration of externalities such as emissions, noise, equality or city structure. Engineers in all-to-often “stove-piped” groups would conduct feasibility studies within their relatively narrow field of expertise, identify problems in that domain, and then spend significant resources to drill down and solve those problems. For a majority of the past



century this design paradigm sufficed to produce excellent products, and the comparatively slow rate of adoption of these products by markets enabled natural feedback loops for regulators or later versions of the products to address emergent externalities.

Today, however, the rapid diffusion of new technologies throughout society and the high level of integration between systems has created new challenges for traditional technology development and implementation approaches. By only considering traditional engineering or business domains during conceptual design, companies may invest significant funds to solve a technical problem only to discover a more significant, potentially show-stopping integration or public acceptance problem after product release. The importance of expanding the system boundary of design problems into other disciplines is a core tenet of modern engineering systems as expressed in *Engineering Systems: Meeting Human Needs in a Complex Technological World* [5, p. 16].

*Today... [an] engineer has to interact with a host of socioeconomic complexities and “externalities” – impacts, either positive or negative – that are not a direct part of the artifact or even a self-contained system or process under consideration. It used to be that engineers ... did not worry about [externalities] in their designs. Today, these externalities must be factored into the design process.*

Examples of setbacks or failures in major new technologies as a result of unconsidered non-technical challenges are surprisingly common, especially in the aerospace sector. For example, The Concorde and Supersonic Transport programs never fulfilled expectations and ultimately failed not solely because of technical challenges, but in large part because aircraft noise was not a primary focus of the first generation aircraft development [6], [7]. Even in the burgeoning UAS industry, public acceptance of UAS operations and privacy concerns have created challenges for widespread adoption, and regulatory update processes have been too slow to keep up with developments in some UAS applications [8]. Beyond aviation, products such as autonomous cars and wind turbine towers have also faced implementation set-backs due to consumer or bystander concern resulting in public action. Finally, the unequal accessibility of some areas of the world or population segments to new technologies such as computers or smart phones has exacerbated inequality spurring social equity and environmental justice concerns [9].

Startups, large companies and venture capital firms have all invested millions of dollars in new technologies that ultimately did not (or have not as of yet) achieve expectations, in many cases because there was a failure to consider factors in conceptual design beyond technological feasibility and regulatory compliance. Considering the rapid pace of technological diffusion and the increasing interconnectedness of systems, a new approach is necessary for early-phase conceptual design, and particular requirements definition. This new approach should use “first principles” to review not only technical feasibility and regulatory compliance, but also operational integration with existing systems (i.e. technology infusion), social acceptance of the technology, market demand patterns, and environmental justice, among others.

Such an approach, which may be described as utilizing *systems thinking*, could enable innovators, decision makers and investors to better identify product requirements during conceptual design, and avoid potentially costly revelations following the initial prototype or product implementation. It was with this consideration that a systems-level analysis approach was developed in this thesis and applied to ODM Aviation.

### ***1.3 Scope***

The purpose of this thesis is to assess the operational potential for ODM Aviation networks in metropolitan regions by assessing the technological maturity, regulatory environment, market opportunity, airspace management techniques and associated externalities, among others factors.

This thesis is not focused on developing UAS or ODM Aviation technologies or vehicles. There are over 15 companies at the present day, as well as NASA, diligently working to mature distributed electric propulsion systems, autonomous flight controls and energy storage techniques, among many other technologies associated with new ODM aircraft. In fact, this thesis seeks to be as technology and vehicle *agnostic* as possible when assessing the operational potential and constraints for ODM Aviation markets. The findings of this thesis may therefore be useful to in developing requirements for technologies to support this field.

While ODM Aviation and UAS technologies may ultimately be implemented around the world, this thesis specifically reviews opportunities and challenges these vehicles may experience for operation in the United States. To this end, the primary case study presented in this research focuses on Southern California as an early adopting market. Therefore, while the findings of this thesis may be informative to the potential implementation of ODM Aviation networks around the world, there may be factors, or attributes, that vary widely between different cities and countries and dramatically influence the operational feasibility of ODM Aviation networks.

### ***1.4 Research Questions***

This thesis was motivated by the anticipation of an emerging On Demand Mobility for aviation market and the desire to identify operational constraints for such a network. To formalize this inquiry, the following three research questions were developed:

1. **CONSTRAINTS**: What are the critical technological, operational, regulatory, business or system interface factors that may constrain or prevent ODM Aviation implementation in the United States?
2. **EXTERNALITIES**: What externalities may originate from the proliferation of ODM Aviation networks in the United States, what potential impacts may they have on society, and how may they in turn influence ODM Aviation?
3. **POTENTIAL MITIGATIONS**: What technology or policy options may be considered in both the near and far-term to address the binding constraints and negative externalities of ODM Aviation implementation in the United States?

In order to address these three research questions, a holistic, systems approach must be developed to consider the whole concept of operations for ODM Aviation networks and identify the most salient potential challenges for the implementation of such a technology in American metropolitan areas. This approach represents a new way to develop requirements during early-phase conceptual design.

## 1.5 Methodology

Numerous studies have previously been conducted concerning various operational aspects of ODM Aviation. High fidelity market models were developed to forecast promising demand areas and applications for the new ODM vehicles [10], [11]. Proposed ConOps for ODM Aviation missions were also reviewed to identify various vehicle, noise and infrastructure constraints [12], [13]. Finally, numerous law review articles have explored regulatory and legal factors that may influence the operation of UAS and ODM aircraft at low altitudes.

The approach developed through this thesis to assess the operational potential for ODM markets differs from these previous approaches. While each of the above studies conducted an in depth assessment of ODM Aviation in a single domain (business, operations, or regulations), this thesis assesses operational potential by holistically reviewing all of these fields in relation to one another, as well as considering social, environmental and system integration factors.

Figure 2 presents a flow block diagram displaying the principal steps of the approach developed in this thesis. The case study in this thesis applied this approach to ODM Aviation operations in Los Angeles and Southern California. To begin, potential early adopting markets of ODM Aviation services were identified in the Los Angeles area using commuting, income, household valuation and current helicopter charter service information. Nine “reference missions” were defined that characterize a diverse set of ODM Aviation requirements in terms of mission range, demand, ground population density, infrastructure availability and airspace interaction, among others. Three additional reference missions were also created with randomly generated origin and destination points address possible selection bias in the reference mission definition. Any number of reference missions could have been defined or randomly generated, however twelve was deemed a sufficient number to capture the variability of possible ODM mission attributes for the L.A. case study.

Next, a concept of operations (ConOps) was drafted for each reference mission. The ConOps defined the activities completed by the customer and ODM aircraft from the moment the customer ordered the service to the moment the customer reached their destination. The ConOps therefore included customer ground transportation, aircraft staging and ferrying, customer boarding, flight path planning, air traffic control interaction and aircraft charging, among others. The ConOps defined operations from a vehicle agnostic standpoint assuming basic requirements, such as VTOL capabilities, rather than baselining performance on a specific vehicle.

Having defined ConOps for the twelve reference missions, the next step analyzed each mission through multiple domain lenses. Researchers conducting *enterprise architecting* on the largest systems in society have found that adopting multiple design perspectives (lenses) effectively reduces complexity and increases the likelihood of uncovering novel factors [14, p. 14]. Adapting this approach for the conceptual design of novel ODM technologies, the ConOps were first assessed through the traditional engineering lenses of technical feasibility and regulatory compliance. Next, the ODM Aviation networks were evaluated with respect to numerous other domains including community acceptance of operations, interface challenges with systems such as air traffic control, ground infrastructure and ground-based transportation, and environmental impact. This step provided a holistic view of the potential operational challenges ODM Aviation networks face, but did not review any one challenge in significant detail.

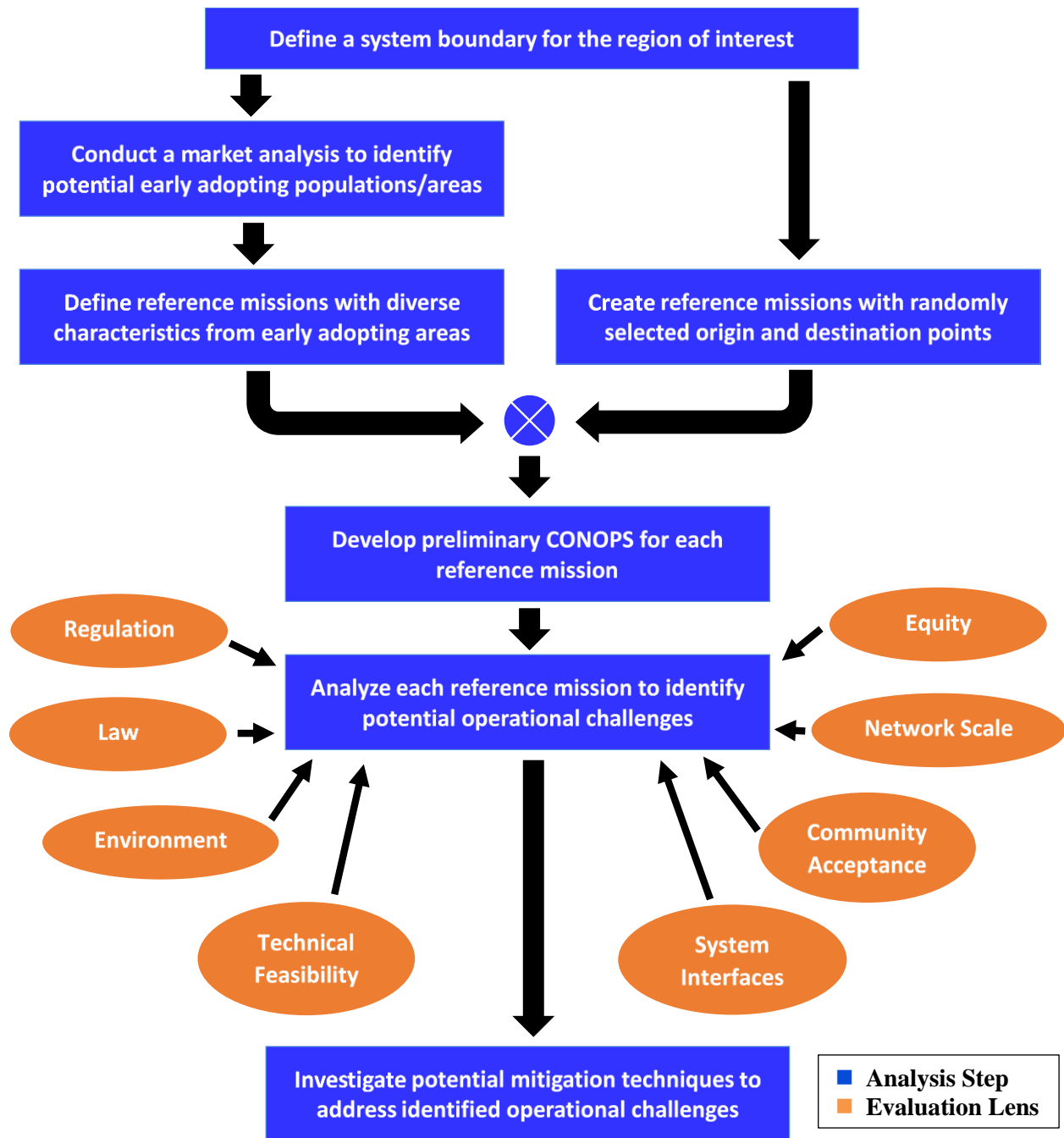


Figure 2. Flow block diagram displaying the first principles analysis approach developed in this thesis to assess the operational potential for ODM Aviation networks in U.S. metropolitan areas.

Therefore, the final step of the analysis approach prioritized the identified challenges, investigated the most severe constraints in greater depth and then evaluated potential mitigation techniques to address binding constraints. Potential mitigation techniques were devised through a variety of approaches. First, proposed mitigation techniques were collected from the literature where available. Secondly, the challenges identified in this thesis were presented on numerous occasions to stakeholders in the ODM Aviation industry who proffered mitigation options based upon their

expertise. Finally, inspired by the “backcasting” methodology developed by numerous authors creating environmental regulation and policy pathways, this analysis approach projected the ideal future scenario for ODM Aviation networks as proposed by the industry, and then sought to backcast what mitigation approaches were necessary to achieve that future.

## ***1.6 Thesis Overview and Organization***

New technologies, such as UAS or ODM Aviation networks, often face significant implementation challenges due to operational constraints, system integration requirements and emergent negative externalities that were not considered during conceptual design. This thesis seeks to develop a systems approach to evaluate potential ODM Aviation concepts of operation and identify crucial, non-technical interface challenges that may not have previously been considered by the industry.

The approach developed relies upon first principles to identify potential constraints while making as few assumptions as possible. It is proposed that starting with fundamental principles (instead of immediately employing highly detailed modeling and simulation) reduces the signal to noise ratio and enables a decision maker to resolve fundamental challenges that may have been obscured or missed in a more detailed, but less holistic analysis. Furthermore, while some researchers have created complex demand models and simulated tens of thousands of operations, the approach taken in this thesis minimizes resource utilization and only “drills down” to higher fidelity investigations and models once the most salient challenges are identified.

Finally, this thesis attempts to capture the time dependent nature of operational challenges with respect to the scale of the ODM Aviation network. The explicit consideration of implementation scale impacts further enables decision makers to make research priority and investment decisions during conceptual design. The review of ODM Aviation presented in this thesis expands traditional systems engineering for early phase conceptual design by adding operational, human factors, regulatory, environmental and ethical considerations.

This thesis is organized to follow the steps of the analysis approach presented in Figure 2 and evaluates potential ODM Aviation operations as follows:

### **Chapter 2: Background and Literature Review**

The concept of on demand or personalized air transportation is not a recent development. Chapter 2 reviews numerous previous attempts to develop the technologies and business approaches necessary to support intra-urban air transportations services. These historical efforts form the underpinnings of the current programs in ODM Aviation. Chapter 2 also reviews the recent successes of the ground-based ODM markets and reviews how three enabling technologies (electric aircraft, telecommunications and autonomy) may allow for the successful expansion of these services to aviation. Existing approaches for early-phase conceptual design and requirements engineering are investigated to identify gaps that may be addressed by the systems-level analysis developed in this thesis. Finally, literature on externalities and their influence on new technology adoption and proliferation is presented.

### **Chapter 3: ODM Aviation Market Opportunities and Case Study Definition**

While ODM Aviation may potentially reach a large total addressable market in the far-term, the near-term implementation of these new services will focus on specific high-value applications and business concepts. Chapter 3 identifies high-value, early-adopter ODM Aviation markets and

services for the industry as a whole, as well as in Southern California. Furthermore, although externalities have typically not been considered during conceptual design, Chapter 3 investigates how ODM operators may be able to leverage positive externalities of urban air mobility to garner additional benefits (profits) and hasten near-term adoption.

#### **Chapter 4: Los Angeles Case Study Reference Mission Definition**

Chapter 4 considers the market opportunities and positive externalities presented in Chapter 3 in order to define 12 reference missions in Southern California, centered on the Los Angeles basin. The missions represent multiple types of markets, flights of diverse range, duration, demand and airspace congestion, access to varying levels of ground infrastructure, and diverse requirements for flight profiles.

#### **Chapter 5: ODM Aviation Operational Constraints Identification**

To identify the operational constraints of ODM Aviation, Chapter 5 defines a concept of operations (ConOps) based upon near-term aircraft capabilities and mission concepts and applies the ConOps to each of the 12 reference missions. By reviewing the reference mission ConOps, 20 challenges were identified for ODM Aviation network operations that may challenge the successful implementation of such services. These challenges were condensed into five *constraints* and three *issues* based upon similar attributes and their relative severity. The five ODM Aviation constraints were evaluated for their sensitivity to growth in ODM Aviation network scale (number of operations) to understand how they may vary from the near-term to the long-term.

#### **Chapter 6: Legal and Regulatory Considerations for Low Altitude Aircraft Operations**

One of the greatest near-term challenges for ODM Aviation in the U.S. is the set of regulatory and legal considerations that may limit or prohibit certain types of aircraft operations or operations in specific areas and airspaces. Chapter 6 is dedicated to reviewing the nation-wide uncertainty surrounding low altitude aircraft operations and the potential constraints the FAA, states, local municipalities and private landowners could levy on ODM and UAS flights in these airspaces by means of regulations or legal action. Local municipality and state regulations that impact airport (or heliport) location and usage are discussed in Chapter 7 rather than Chapter 6.

#### **Chapter 7: Review of Operational Constraint Mitigation Approaches**

Chapter 7 reviews a variety of mitigation approaches for the ODM Aviation constraints and issues. The near-term implementability of each mitigation proposal was first evaluated for a small-scale ODM Aviation network. The influence of the mitigation approach on the network was assessed, and the degree to which it may lessen or remove the constraint was considered. Furthermore, ancillary effects of the mitigation approach on other constraints (perhaps beneficial or detrimental) were investigated. Finally, the capacity of the mitigation technique to scale with increasingly dense ODM networks was investigated.

#### **Chapter 8: Conclusion**

Chapter 8 reviews the three thesis questions posed in Section 1.4 and provides direct answers based upon the findings of the research. The limitations of the research conducted in this thesis are presented and future work is discussed.

## **2 Background and Literature Review**

*Since it seems inevitable that within the foreseeable future the proportion of the population that flies regularly will multiply many-fold, and the proportion that has flown will increase several-fold, one would guess that the form-shaping effects of air travel have only begun to be felt. We are only at the beginning in vertical takeoff craft and helicopter service, and local travel by air is therefore in its most primitive stages. ... Even though local air travel may not serve the huge volumes required by high-density zones, since both air and land modes will operate and exist side by side, it is clear that pricing, licensing and other volume controls must be devised as technical capacity restraints become operative.*

- *Form and Structure of the Metropolitan Area* [15, pp. 180–181]

### **2.1 Historical Underpinnings of On Demand Mobility for Aviation**

As evident in the quote from 1966 at the beginning of this chapter, the concept of short-distance, intermodal travel using aircraft as the central leg, or *urban air mobility*, is not a recent development or dream. Rather, transportation engineers, entrepreneurs and science fiction writers have all predicted futures where flight becomes a standard form of conveyance, even for short trips within a single city.

This section provides a brief review of the various visions of urban air mobility, the attempts to implement them, and the factors that inhibited their ultimate success. The precursor industries and technologies developed through these historical efforts constitute the historical underpinnings for modern ODM Aviation and contribute perspective to the current proposals.

#### **2.1.1 The Early Years of Air Transportation**

Due to the rudimentary capabilities of aircraft in the early 20<sup>th</sup> century, the pioneers of aviation were initially limited to providing short distance urban air transportation services. Lacking aircraft with sufficient range, speed or reliability to carry passengers between any but geographically close cities, some early airlines began commuter services between sections of the same town or over geographic barriers such as rivers and bays that separated two areas. For example, on New Year's Day, 1914, Tony Jannus piloted the first commercial airline flight in the United States carrying passengers 23 miles from St. Petersburg to Tampa over the Tampa Bay.

The founder of the St. Petersburg–Tampa Airboat Line, Percy Fansler, made the following statement about the historic flight: “the Airboat Line to Tampa will be only a forerunner of greater activity along these lines in the near future... what was impossible yesterday is an accomplishment of today... while tomorrow heralds the unbelievable” [16]. Today, over a century after this historic first flight, commercial airliners transport more than 3.5 billion passengers a year and support a substantial percentage of world commerce [17]. While this accomplishment would certainly be unbelievable to Fansler, the dream of urban air mobility has not become reality and scarcely progressed beyond the services offered by these early airlines.

The rapid proliferation of airlines and advancement of aircraft capabilities in the early years of air transportation buoyed widespread speculation for how air transportation could become an everyday phenomenon and change the fundamental ways individuals live their lives. However, as aircraft technologies improved, short range, intra-urban operations were discarded in favor of

longer distance, more profitable routes. Urban air transportation would not be seriously reconsidered as a market until the availability of the helicopter.

Although the airline industry moved away from intra-urban operations resembling proposed ODM Aviation concepts, the dream of short range personal air transportation was kept alive in the media and science fiction of the day. Arthur C. Clarke shared such sentiments in his first published short story in 1946:

*For the culture of cities, which had outlasted so many civilizations, had been doomed at last when the helicopter brought universal transportation. Within a few generations the great masses of mankind, knowing that they could reach any part of the globe in a matter of hours, had gone back to the fields and forests for which they had always longed. [18, p. 38]*

### **2.1.2 Urban Air Transportation of the 1960's and 70's**

The first attempts to foster urban air transportation markets began in the 1950's and peaked during the 1960's and 70's following the availability of turbine-powered commercial helicopters. The post-World War II economic boom resulted in the dramatic growth of U.S. metropolitan areas and the appearance of suburban developments. Furthermore, rapid advancements in helicopter technologies were driven by military investments during the Korean War and filtered into the commercial markets providing safer and more capable vehicles. Empowered by these new technologies and recognizing emerging market opportunities as urban sprawl and ground congestion increased, the aviation and transportation communities dedicated substantial resources to bring air carrier and air taxi services to major U.S. cities [19].

Following in the path of the early aviators from 40 years earlier, the first helicopter air carriers began as air mail services in 1947 supported by subsidies from the U.S. Government. These companies carried their first commercial passengers in 1953. By 1963, four scheduled helicopter carriers were in operation in Los Angeles, San Francisco, New York, and Chicago earning over 80% of their revenues from passenger ticket sales [20]. These companies primarily provided services between major airports, or between an airport and the downtown Central Business District (CBD). In some cases these companies also provided charter services and private business bookings to diversify their income.

Operations grew dramatically during the 1960's from under 400,000 annual passengers in 1962 to over 1.2 million passengers in 1967. By all indications, a budding new industry was emerging. While new helicopters and aircraft attracted customers, operators found that investments in new helipad infrastructure in congested areas most dramatically increased demand for their services. A helicopter operator in New York experienced a 50% increase in revenue passenger miles over the course of a single year as a result of opening service to the rooftop helipad of the Pan Am building [20]. The Pam Am heliport and other innovative takeoff and landing infrastructure used by intra-city aircraft operators in New York City are pictured in Figure 3.

In addition to the four scheduled helicopter air carriers, over 100 helicopter-based air taxi operators were in business in 1976 providing pre-booked, intra-city transportation [19, p. 38]. Perhaps most remarkable, an airline named "Air General" set up a network of over 70 heliports in Boston (many in motel parking lots or private greenspaces) and offered a commuter service from 1962 to 1969



carrying over an estimated 100,000 passengers in this period. Air General did not fly scheduled flights, but rather would operate based on a reservation system allowing customers to request flights in as little as 30 minutes prior to a desired pickup time [20]. Therefore, Air General represents the first ODM Aviation company. It operated for nearly a decade, over 50 years before the current generation of aspiring companies will be able to re-enter the market. Impressively, Air General was able to achieve relative success as an ODM Aviation operator without the capabilities of modern computing, telecommunications and aircraft.



Figure 3. New York Airways conducting helicopter service from the Pan Am building (*left*) and with a Twin Otter operating from a short runway in the boroughs (*right*). *Pan Am image retrieved from [21], and Twin Otter image retrieved from [22, p. 66].*

Although these early operators were ultimately forced to significantly reduce or terminate operations due in large part to community acceptance and financial challenges (effectively ending public, urban air transportation for a half century), the lessons learned by these businesses and the research, regulatory and societal impact from their operation significantly influence the opportunities and challenges ODM Aviation faces today. The nearly two decades of aircraft-based, intra-city transportation attracted significant public and government attention to the potential of aircraft to constitute a new form of transportation, reduce congestion and overcome the geographic constraints of ground mobility modes.

For example, city planners in Los Angeles conducted a detailed analysis in 1973 to determine how increasing numbers of intra-urban flights and helipad infrastructure could be supported by the city. Their study found that local governments and FAA regulators needed to explicitly consider noise, pollution, the public good and land use before approving any new helicopter air service provider. Furthermore, their study recommended a host of actions for local government to take, such as treating helipads as public utilities, resolving the legal and regulatory jurisdictions of low altitude airspace, and including urban air transportation in a city's strategic development plan [23]. These recommendations are, in most cases, as applicable today as they were at their time of writing.

Figure 4 displays example concepts from studies in the 60's and 70's displaying how urban air transportation ground infrastructure could be integrated within cities. As can be seen, a key focus

of the planners was providing effective intermodal linkages between the air, surface and sub-surface transportation modes.

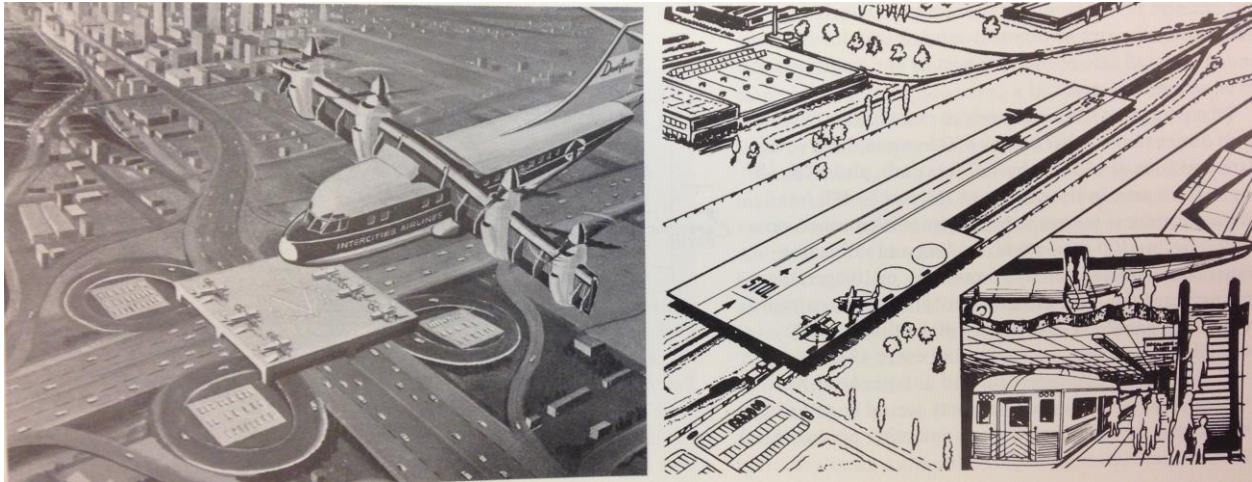


Figure 4. Examples of intermodal ground and aviation infrastructure proposed in 1973 to support expanded intra- and inter-city aviation operations. These images were collected by Glen Gilbert [22, p. 88] and strongly resemble contemporary ODM Aviation ground infrastructure proposals from NASA [13].

On the federal level, the DOT and NASA also commissioned multiple studies to assess the potential for helicopters and tiltrotor vehicles to revolutionize transportation. While these studies in general agreed that V/STOL (vertical/short takeoff and landing) aircraft presented a compelling case for implementation over the latter half of the 20<sup>th</sup> century, they also identified a number of challenges that needed to be resolved before aircraft-based, intra-city transportation could become possible [19], [20]. These challenges included:

- Availability of geographically distributed ground infrastructure co-located with areas of customer demand
- Integration of urban air transportation operations with Air Traffic Control (ATC) and the potential need for a new, automated ATC system to manage airspace below 3000 ft
- Achieving community acceptance of vehicle noise and the need for quiet rotor vehicles
- Development of a computerized customer booking and demand scheduling system

This thesis will display which of these challenges have been overcome since the 1970's by the appearance of new technologies, which challenges continue to exist today, and challenges that were never identified by these early studies but may limit the operational potential for ODM Aviation.

Finally, the last impact of the nation's foray into urban air transportation during the 60's and 70's is the public impression of the industry that emerged. These early operations were often quite expensive and primarily appealed to businesses and wealthy individuals. Therefore, while only a few million passengers experienced the benefits of urban air transportation, the general public often experienced the negative externalities associated with these operations. For example, new helicopter pads and the expansion of flights to new areas were heatedly protested by local residents

and community groups concerned about safety and noise [24]. A series of high profile helicopter accidents exacerbated these fears and ultimately led to the closure of Los Angeles Airways as well as the discontinuation of public helicopter services in New York to the Pan Am helipad or any Manhattan helipad not on the water's edge [25]. Some residual effects of these negative experiences are still apparent today as communities express concern about the safety, acoustic signature, and privacy of overhead helicopter, unmanned aircraft system (UAS), or ODM aircraft flights.

### 2.1.3 Helicopter Charter Flight Networks

Although the scheduled helicopter air carrier and air taxi helicopter networks of the 1960's and 70's did not prove to be sustainable, helicopter charter services have continued to operate, and in some cases thrive, in various large cities around the world. The most extensive helicopter charter networks today exist in São Paulo, New York City, and Los Angeles. Each of these areas have populations of greater than ten million people spread out over hundreds to thousands of square miles. While these three cities dramatically differ in geographic features, weather, city structure and public transportation, among other factors, the sheer size of their population has led to some of the worst traffic congestion in the world.

As a result, helicopter charter services have sustained a business providing private air transportation for corporations and the wealthy. Many of these helicopter operators also conduct a significant number of sightseeing flights to diversify their income. Table 1 displays the number of helicopter service providers in each of these three cities and the types of services they offer to the public. Furthermore, an estimate of the number of operations that occur annually in each city is provided where a credible number could be found.

Table 1. Current helicopter charter and sightseeing operations in major world cities.

| Area          | Number of Helicopter Operators | % offering Charter Flights | % offering Sightseeing Flights | Total Annual Operations |
|---------------|--------------------------------|----------------------------|--------------------------------|-------------------------|
| Los Angeles   | 11                             | 91%                        | 91%                            | Unknown                 |
| New York City | 7                              | 100%                       | 57%                            | >75,000 [26]            |
| São Paulo     | 13                             | 100%                       | Unknown                        | >70,000 [27]            |

These helicopter charter flight networks represent the current state of the practice for urban air transportation. While these operators are not considered “on demand mobility” as they typically require significant booking lead time and operate on relatively fixed routes between airports and other limited ground infrastructure, some operators are beginning to adapt greater flexibility in their services. The helicopter network in São Paulo should be especially noted as breaking new ground on ODM-like services. In this megalopolis, some sources report that there are now over 400 helicopters traveling between a network of more than 250 helipads [28]. One potential pathway for ODM Aviation networks to develop is to evolve from the current helicopter charter services in cities such as São Paulo building upon their extensive operational experience.

As the primary remaining form of urban air transportation, these helicopter charter operators (alongside law enforcement and medical services flights) are also a cause of controversy concerning noise, pollution and privacy from the public. Helicopter operations in Los Angeles

have been a source of public ire for years ultimately resulting in Congressional action mandating a FAA study on the issue [29], [30]. Similarly, after experiencing dramatic growth in the number of helicopter tour operations in New York City between 2008 and 2013, negative public sentiment from these operations resulted in a mandate from the local government to reduce tour operations by 50% between 2016 and 2017 [31], [32].

The experience of the helicopter charter operators in managing public concern may foreshadow future challenges ODM Aviation operators may experience.

#### **2.1.4 Inter-City and Commuter Airline Regional Flight Networks**

Although ODM Aviation is primarily focused on providing air transportation services within a single metropolitan area including its surrounding satellite cities and suburbs, a variety of attempts have been made to develop regional *inter-city* flight networks. The à la mode term for these types of missions is “thin-haul” services, and they have historically been operated by “commuter airlines.” Industry and government interest in short range, inter-city air transportation is responsible for much of the VTOL technological development that occurred since the 1970’s. Furthermore, both successful and unsuccessful attempts to operate inter-city services provide insight into additional challenges that may be relevant to ODM Aviation.

Figure 5 displays a 1970’s concept aircraft to provide VTOL commuter service between closely paired cities, or perhaps even from a satellite city into the central business district. Figure 6 presents major NASA technology development programs over the ensuing 40 years that sought to develop such vehicles. While none of the proposed concepts matured into an aircraft certified for commercial use, the technologies that were developed laid the foundation for the distributed electric propulsion, tiltrotor aircraft that are currently being considered for ODM Aviation applications.

The efforts of inter-city aviation companies also prompted regulatory action. Anticipating the implementation of VTOL capable aircraft for inter-city flight networks, the FAA developed an advisory circular in 1991 specifically for vertiport design. Within this advisory circular, the FAA directly recognized the potential value these new forms of aviation may bring to the industry by saying [33]:

*Tiltrotor technology offers a viable city-center to city-center air transportation capability and air transportation system capacity enhancement. The potential payback exceeds by a large margin that offered by any other technology presently identified or under development.*

Although the expected operation of VTOL inter-city links never materialized and the FAA cancelled the advisory circular in 2010, it serves as an important precedent for ODM Aviation operations.

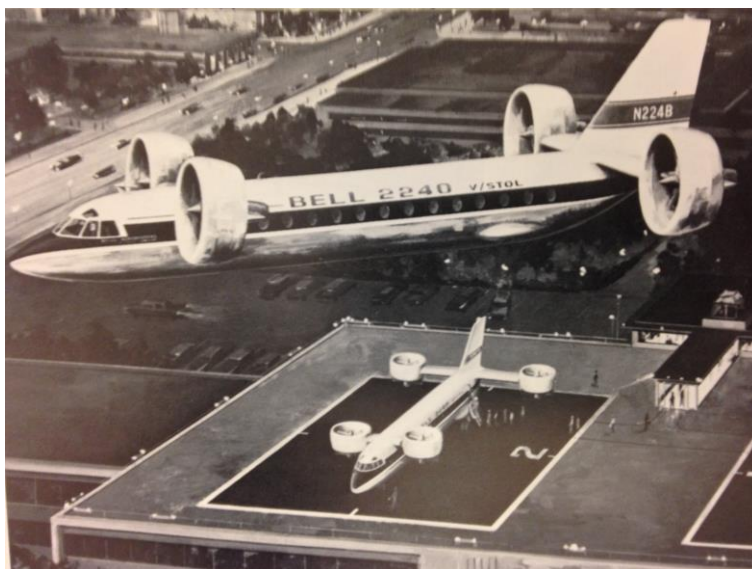


Figure 5. VTOL commuter service concept for operations into city centers or between closely paired cities. *Image retrieved from [22, p. 67].*










|  |  |  |  |   |
|--|--|--|--|---|
| <p><b>1987-1991:</b> Civil Tiltrotor Missions and Applications: Phase I &amp; II (Boeing, Bell, Boeing Vertol, NASA)</p> | <p><b>1995:</b> Report to Congress: Civil Tiltrotor Development, Vol. I &amp; II</p> | <p><b>2000-2003:</b> Runway Independent Aircraft Studies (Bell, Boeing, Sikorsky; NASA funded)</p> | <p><b>2004-2005:</b> NASA Heavy-Lift Rotorcraft Systems Investigation</p>            | <p><b>2009-2011:</b> Modeling High-Speed Civil Tiltrotor Transports in the Next Generation Airspace (SAIC et al; NASA funded)</p> |
|                                       |   |                 |  | <p><b>2009:</b> Advanced Vehicle Concepts and Implications for NextGen (Sensis et al; NASA funded)</p>                            |
|                                       |   |                 |  | <p><b>2009:</b> Aircraft System Analysis of Technology Benefits to Civil Transport Rotorcraft (Boeing; NASA funded)</p>           |
| <ul style="list-style-type: none"> <li>• 8-75 pax</li> <li>• 270-300 kts</li> </ul>                                      | <ul style="list-style-type: none"> <li>• 40 pax</li> <li>• 315 kts</li> </ul>        | <ul style="list-style-type: none"> <li>• 80, 90, 120 pax</li> <li>• 310-350 kts</li> </ul>         | <ul style="list-style-type: none"> <li>• 120 pax</li> <li>• 350 kts</li> </ul>       |    |
| <p><b>Base R&amp;T</b></p>   | <p><b>Short-Haul Civil Tiltrotor / Aviation Systems Capacity</b></p>                 | <p><b>Vehicle Systems</b></p>  | <p><b>Fundamental Aero</b></p>   |   |

Figure 6. NASA technology development programs for VTOL aircraft 1987-2011. *Image retrieved from AHS Vertiflite [34, p. 32].*

Beyond aircraft technologies and regulations, a variety of commercial entities have attempted to operate inter-city flight networks with either scheduled or on-demand business plans. Although these operators achieved varying levels of success, the lessons taken away from their efforts may influence the business models of future ODM Aviation service providers.

Beginning with a successful example, a variety of commuter airlines have thrived in the United States providing short distance city to city links where either demand is too small for mainline service, or distances are too short to justify the use of large aircraft. These airlines typically operate under Part 135 using aircraft that have a capacity of nine passengers or less. One of the most successful commuter airlines, Cape Air, shares numerous characteristics with proposed ODM networks. First of all, 98% of Cape Air's non-government subsidized routes have a range of 100 miles or less with 46% of these routes being 50 miles or less [35]. While Cape Air does not use VTOL aircraft and does not conduct intra-urban operations, a majority of their routes are comparable to projected ODM Aviation missions.

Secondly, Cape Air and the commuter airlines operate as *scheduled* operators under Part 135. This means that their routes and departure times are published ahead of time rather than being generated dynamically in response to demand. While ODM Aviation, by the very nature of its name, ultimately seeks to achieve dynamic route and departure scheduling, Cape Air is able to provide nearly proximate ODM capabilities due to the frequency of its departures. On some routes during high demand periods Cape Air may have flights leaving as often as every fifteen minutes.

On the other hand, an unsuccessful attempt to develop an inter-city flight network was the Small Aircraft Transportation System (SATS) research project of the FAA and NASA in the early 2000's, and the very light jet (VLJ) market it fostered. SATS investigated the potential to use small aircraft and VLJs to provide air taxi services between general aviation and non-hub airports in the United States. The SATS studies displayed the feasibility of inter-city, on demand aviation networks and numerous new operators and manufactures of VLJs entered the market [36]. Despite the significant investment and initially promising trends for the new VLJ air taxi sector, the financial crisis of 2008 forced many operators and manufactures out of business [12].

While neither the commuter airline nor VLJ air taxi sectors fully represent ODM Aviation networks, they each provide insights into some challenges the industry may face from technical, regulatory and business standpoints. Perhaps one of the most significant contributions of the SATS program was to identify impending ATC scalability and airport congestion problems that could result from a dramatic increase in air taxi services [37]. The research addressing these challenges proposed numerous potential mitigations that are equally applicable to ODM Aviation today. Finally, similar to charter helicopter operators, currently sustainable commuter airlines (such as Cape Air) may represent another pathway through which ODM Aviation networks could evolve.

### **2.1.5 Personal Air Transportation**

The final precursor for ODM Aviation networks is the substantial government and private research that has gone into the development of vehicles to provide personal air transportation. The concept of personal air transportation revolves around developing an airborne vehicle that may be used (and was often assumed to be owned) by an individual with basic flight knowledge. A wide variety of transportation modes have been proposed that fall under this banner including flying cars and personal air vehicles. Compared to helicopter charter providers, commuter airlines and VLJ air

taxi operators, the personal air transportation aircraft most closely resemble the projected size and capabilities of proposed ODM Aviation aircraft. Therefore, a brief review of these technologies is in order.

Flying cars, also known as “roadable” aircraft, are hybrid vehicles that may be driven on the roads like normal automobiles but also converted to fly as aircraft. Roadable aircraft have typically been marketed as privately owned assets rather than assets for a transportation service provider or a fractional ownership program. These vehicles have the distinct potential benefit of reducing the impact of the “first mile/last mile” challenge from ground transportation to and from airports as the same vehicle may be used for the entire mission. Numerous companies have sought to develop roadable aircraft over the past half century, though none have produced a certified vehicle. However, Terrafugia, PAL-V and AeroMobil are purportedly approaching vehicle certification in the near future.

Personal Air Vehicles (PAVs), on the other hand, are not certified to be driven on roadways but are intended as private point-to-point air transportation using V/STOL capabilities. NASA stood up the PAV Sector Project in 2003 to support the development of technologies and coordinate industry stakeholders to enable the production of PAVs. Technology road mapping at the time identified community noise and aircraft ease of use as the two most pressing challenges for PAV development and adoption [38]. While progress was made on multiple small aircraft technologies and a variety of companies developed interests in the production of these vehicles, there are not currently any certified PAVs on the market.

### **2.1.6 Concept Revitalization as ODM Aviation**

The emerging PAV and roadable aircraft manufacturers, VLJ air taxi operators, and indeed the entire aviation industry were marred by the financial crisis of 2008 and the proceeding years. However, during this time a suite of new technologies emerged in non-aviation sectors that were recognized to potentially contribute significant value to urban air transportation. These technologies include simplified ridesharing, trip booking, and network load balancing enabled by the proliferation of smart phones, improvement of battery energy density and electric motors, and advancement of automation. A more detailed discussion of these technologies and others is presented Section 2.3.

These new technologies, when coupled with the widespread economic recovery since 2008, have given rise to a renewed interest in urban air transportation by investors, operators and manufacturers. Building upon the lessons learned from all these previous efforts, the new trend is to develop 1-4 passenger, VTOL aircraft that will be operated by a service provider within a metropolitan region to provide on demand mobility offerings. Section 2.2 further discusses the exact form of this proposed new market and its relation to ground-based ODM markets.

Finally, the NASA Personal Air Vehicle Sector Project evolved to support the needs of this emerging industry as the NASA On Demand Mobility Project. Similar to its original function, the program is conducting technological development of distributed electric propulsion aircraft for ODM Aviation and convening the community to develop technology roadmaps and research priorities. As discussed further in Section 2.4, dozens of startups and numerous major industry players have intentions to manufacture small VTOL aircraft for intra-city operations.

## ***2.2 On Demand Mobility and Aviation***

During the 20<sup>th</sup> century, the personal automobile dramatically increased the average speed at which an individual could travel compared to previous modes. As most U.S. families owned their own vehicle, the car was also nearly infinitely available for use. Furthermore, the cost of ownership of an automobile fell steadily throughout the century as manufacturing techniques improved and worldwide competition evolved. These three positive characteristics (high speed, high availability and low cost) allowed the personal automobile to rapidly proliferate society.

However, these benefits of personal car ownership have significantly eroded for modern drivers. Cities have become more populated and the road and highway infrastructure is overburdened in most areas of the United States. This has resulted in congestion that reduces the average speed of automobile travel. It is estimated that road congestion will cost the U.S. economy as much as \$97 billion dollars in 2020 due to lost time and wasted fuel [39]. Parking has also become limited and consumers find their personal vehicle to be less and less available at the time or in the places they desire them. Finally, dramatically increasing oil and insurance prices reduced the economic efficiency of owning a personal automobile [40].

As a result of these challenges of personal car ownership, significant market demand now exists for mobility that could once again increase travel speed, reduce costs, and be more readily available. This demand for enhanced mobility could be met in a variety of ways. Providing a few examples, a new vehicle could be developed that provides an alternative to travel by road, the current highway and parking capacity could be expanded to relieve congestion, or intermodal linkages could be improved to increase the viability and efficiency of public transportation options.

One approach to enhanced mobility that has received particular attention is to more efficiently utilize existing infrastructure by reducing the number of personal vehicles on the road and optimally managing congestion. Many transportation planners, and even some countries, have explored using congestion pricing and other market measures to influence drivers' behavior and more optimally utilize the transportation infrastructure [41]. Furthermore, over the past decade there has been a significant shift in transportation trends to encourage consumers to rely upon mobility provided as a service rather than personal vehicle ownership [42]. This trend has been motivated by the growth of high density metropolitan regions, greater environmental awareness, and the dropping costs for such services.

The willingness of a consumer to forgo the convenience (albeit at a high cost) of their private vehicle depends upon the ability of an alternative transportation option to provide a sufficient level of service. It is this need to provide point-to-point transportation without prior booking and within a short period of the travel request that motivates the concept of *On Demand Mobility* (ODM). Recent advancements in telecommunications capabilities and the proliferation of smartphones has facilitated the emergence of on demand transportation networks of automobiles. The largest of these companies, Uber and Lyft, now provide ODM services in most major U.S. cities. These companies manage fleets of drivers to offer customers high availability transportation at costs competitive to those of private car ownership.

The emergence of a new "sharing economy" in transportation has also significantly reduced costs of some traditional forms of transportation by splitting the expense of asset ownership among multiple individuals or placing the burden of ownership on service providers. Numerous



companies are offering bike sharing and car sharing programs. Online platforms have been used to support the sharing of privately owned vehicles as well. These business models for transportation, though not necessarily mobility as a service, also enable consumers to forgo personal vehicle ownership and access ODM alternatives.

This sub-section introduces the concept of on demand mobility and discusses the significant variability in the concept as presented by various industries and the literature. Ground-based ODM is first reviewed, and then the term is expanded into aviation.

### **2.2.1 Ground-Based On Demand Mobility**

There are a variety of ground-based mobility modes that have historically provided customers with varying levels of service and availability. Trains, buses, and ferries are not considered ODM due to their fixed routes and schedule. However, traditional taxi services in many ways represent the precepts of ODM as they generally provide point-to-point transportation services along dynamic routes set by each customer's needs. Especially in downtown city areas where the network density of taxis is high, the taxi network may be considered ODM and provides near instantaneous service to customers. However, in suburban regions or during low demand hours, the availability of taxi services may be low and customers may need to schedule a ride many hours in advance.

Capitalizing on the proliferation of smartphones, a plethora of new ground-based mobility modes have emerged that represent various shades of ODM. Each of these new business models for ground transportation is briefly touched upon below. Section 2.2.2 reviews how these new ODM business models may or may not be implemented within aviation markets.

- Ridesharing Networks: in ridesharing networks a mobile application or website connects private drivers with passengers who share a common origin and destination point. The driver may choose to pickup and drop-off the passengers and either split the costs of the trip with their passengers or charge a fare. Example ridesharing companies for cars include Carma and Ridejoy.
- Car Sharing Networks: in car sharing networks customers register for membership with a company through which they may rent company owned cars on a pay by time basis. The rental cars are typically geographically distributed throughout areas of high demand and do not require pre-booking, though may be pre-booked in some cases. Example car sharing companies include ZipCar, Car2Go and Maven.
- Peer-to-Peer (P2P) Rental Networks: P2P rental networks support a mobile application or website where individuals may list their privately owned vehicles for rental. From a customer standpoint, a P2P rental network is similar to a car rental company except the assets are spread around private residences. An example P2P rental company is RelayRides (now known as Turo).
- Transportation Network Companies: representing the largest and perhaps most recognizable new addition to the transportation industry, transportation network companies (TNCs) use a mobile application or website to connect passengers with drivers who provide point-to-point transportation with their private vehicles. TNCs therefore essentially operate taxi networks where the parent company does not own the physical

assets, but is responsible for demand management and vehicle routing. The two largest examples of TNCs are Uber and Lyft.

- Transportation Service Providers: transportation service providers furnish the same service to passengers as TNCs, except the vehicles in the network are owned by the company rather than privately owned by the drivers. Current transportation service providers include taxi companies that modernized to mobile or web-based booking. Many current car sharing and TNC entities anticipate transitioning to the transportation service provider model as autonomous vehicles become widely available.

The dozens of new companies that currently provide services within (or between) these five categories of ODM transportation represent extraordinary market potential and command substantial capital. In their efforts to outcompete the field and emerge as profitable entities, many of these companies have invested heavily in research and development to progress the state of the art of autonomy, demand simulation, dynamic traffic assignment, network balancing and smart city integration, among others. Much of this research is directly portable to ODM Aviation networks.

Compared to traditional taxi services, the new ODM providers have developed and implemented transport control algorithms and strategies that increase the efficiency of the network and maximize the utilization of each asset. Fine spatio-temporal resolution geolocation information from the driver's and customers' smart phones enables centralized management of a network-wide pickup and delivery problem considering dynamic factors such as traffic and delays [43]. Some modeling efforts have shown that the cumulative travel time for all vehicles in a coordinated ODM network may be reduced by up to 40% compared to current operations through ride sharing and new routing mechanisms [44]. Such reductions in operation time may have beneficial externalities such as reductions in congestion, emissions and passenger fees.

One of the primary challenges ODM providers and traditional taxi services have faced is the spatio-temporal bias in transportation demand, or the tendency of aggregate customer demand to be directional with a majority of people wanting to travel in only one direction. In ground and air transportation this leads to network imbalance where assets clump in low-demand areas and must take "deadhead," or non-revenue trips, to return to high-demand areas and balance the network. A variety of approaches have been developed to balance automobile transportation networks that may be applicable to future ODM Aviation networks.

First, approaches have been developed to efficiently balance stranded assets from car sharing networks through rebalancing drivers [45], [46]. Secondly, it has been shown that the development of autonomous vehicles significantly increases the viability of ODM networks and simplifies the balancing challenge [47], [48]. Finally, a variety of demand responsive pricing strategies are introduced to curb travel patterns and prevent network asset imbalance [49]–[51].

In addition to these studies addressing some of the operational challenges of ODM networks, the ground ODM community has also sought to confirm many of the predicted environmental and equity benefits of wide scale ODM adoption. These positive externalities are discussed with relation to ODM Aviation in Chapter 3.

### **2.2.2 Air-Based On Demand Mobility**

In comparison to the automobile sector, there has been a “sharing economy” in aviation for substantially longer. This is due to the high cost of ownership and relatively low utilization of aircraft. Private pilots share aircraft costs through fractional ownership schemes, flying clubs with rental aircraft for members, and expense-sharing with passengers. Nonetheless, except for family and friends of pilots, a majority of the public has not had access to personalized air transportation. Some previous attempts to develop ODM Aviation services for the general public in the form of helicopter and VLJ air taxi services were not broadly successful.

As introduced in Section 2.1.6, there has been a renewed interest in providing air-based ODM services. This interest is stimulated in part by the significant progress made by ground-based ODM companies. The five business models outlined for ground-based ODM provide a starting point from which potential ODM aviation networks may be considered. Table 2 presents the five possible business models and discusses the adaptability of each model to the aviation sector considering the current market and regulatory conditions. Red cells indicate business models that are not appropriate for aviation, orange cells are business models that face significant challenges for implementation in aviation, and green cells are those business models that are already implemented or may be readily implemented in aviation.

From Table 2 it may be seen that the only business approach that provides aircraft-based ODM services to the average citizen (who are not pilots) is air transportation service providers. Aircraft sharing networks and P2P aircraft rental networks are fundamentally restricted to serving the roughly 600,000 certified pilots and therefore do not represent viable approaches to support urban ODM Aviation.

With the goal of making ODM Aviation service available to as much of the public as possible, the use of helicopters or development of new VTOL capable vehicles is absolutely necessary to remove the constraint of operating only from airports and enable the pickup and drop-off of passengers closer to the centers of demand. Simulation of ODM Aviation networks in Germany has shown that the willingness to pay (market demand) for such services is strongly correlated to the first mile and last mile ground transportation distance an individual must take to get to and from the aircraft departure and arrival point [52].

Considering this, aircraft-based ODM shall be defined in this thesis as multi-modal, point-to-point transportation within a metropolitan area provided by a service provider utilizing an aircraft as the central leg of the mission. The scope of ODM Aviation has been limited to metropolitan areas as a threshold density of consumer demand is necessary to support a network of aircraft of sufficient scale to provide service on an on-call, on demand fashion. It is anticipated this level of demand will only exist in metropolitan areas, and air transportation services in rural areas are more likely to operate as an a priori booked air taxi service. In this definition an aircraft is not limited to fixed-wing vehicles but includes helicopters, tiltrotors or other flight vehicle.

Table 2. Overview of potential challenges for adapting successful ground-based ODM business models in the aviation community.

| ODM Business Model               | Adaptability to Aviation  |
|----------------------------------|---|
| Ridesharing Networks             | A variety of companies such as AirPooler and Flytenow recently attempted to organize aircraft ridesharing networks where private pilots may accept passengers who split the costs of operation with the pilot. However, the FAA considered pilots participating in this network as conducting commercial operations making this business model infeasible for aviation.   |
| Aircraft Sharing Networks        | Aircraft sharing networks are already well established in aviation, albeit currently only accessible to individuals with pilots licenses. Flying clubs and other aircraft rental services are examples of such networks. Furthermore, fractional ownership or membership programs such as jet cards are variants of aircraft sharing networks.  |
| Peer-to-Peer Rental Networks     | The author is not aware of any formal P2P aircraft rental networks. However, the informal sharing of privately owned aircraft is common and there do not appear to be restrictions to aircraft sharing if the renter is certified to pilot the aircraft.  |
| Transportation Network Companies | Under current regulations, it would be unlikely a TNC could succeed in aviation due to the lack of commercial pilots with Part 135 certifications. TNCs have been successful for ground transportation because any licensed driver is legally allowed to carry passengers in their private car. However, in aviation private pilots are not approved to carry revenue passengers in private aircraft. A TNC composed of only existing part 135 operators would be highly constricted in operations and profitability. |
| Transportation Service Providers | Under this business model company owned aircraft are operated by company-hired Part 135 pilots, or potentially autonomous pilots in the future. Previous companies that attempted to provide VLJ air taxi or on-demand helicopter services may be considered as ODM transportation service providers. Prospective ODM Aviation service providers have indicated this is the business model they intend to operate under.  |

Beyond representing a significant market opportunity for manufactures and service providers, ODM Aviation has been proposed to provide a variety of benefits to consumers, urban planners and cities. Table 3 displays a summary of the potential benefits and positive externalities of intra-city air transportation.

Table 3. Potential benefits and positive externalities of ODM Aviation in metropolitan regions.

| <b>Potential Benefit</b>                                  | <b>Description</b>  |
|---|---|
| Diversified Mobility Options                              | ODM Aviation will offer a novel new transportation option to citizens in a city. The availability of high speed, uncongested transportation may change the way people live, work and play.  |
| Expanded Mobility Reach                                   | Operating at speeds more than triple that of the average motor vehicle and avoiding ground congestion, ODM Aviation can increase the land area accessible to commuters in a city by up to 10x. This may support cities to continue to grow economically even though high property values and insufficient road capacity have historically limited further physical growth of the city [53].   |
| Transportation Capacity in the 3 <sup>rd</sup> Dimension  | As cities become more densely populated, the percentage of land dedicated to roads and parking increases (by some estimates beyond 30%), yet congestion becomes more severe [54]. ODM Aviation may remove trips from the surface lessening congestion, and may increase total transportation capacity into a region while requiring negligible dedication of additional surface land area.  |
| Transportation Network Resiliency                         | Air transportation is a “nodal” network as opposed to ground transportation which is a “linear” network. This means that an aircraft may fly between any airport or helipad in an ODM network and easily land at a nearby node if the target node is unavailable. This adds resilience to a city’s transportation portfolio as in emergency situations, such as an earthquake, nodal networks are far more robust than road networks which may be shut down by damage to the road at any one point.   |
| Flexible Networks with Modest Infrastructure Requirements | Compared to rail, highway or airport infrastructure costs, VTOL infrastructure is multiple orders of magnitude less expensive. Furthermore, ODM Aviation networks are highly flexible due to their nodal nature. Constructing a new takeoff and landing area in a region automatically connects it to every other node in the network. This allows ODM Aviation to begin services in a new area quickly, or easily transfer services to new developments [20]. John Wolf of Cape Air stated this quality as “build a mile of road and you can drive one mile; build a mile of runway and you can go anywhere” [35]. |
| Evolving City Structure                                   | Trains, cars and buses have dramatically influenced city structure through their introduction enabling citizens to live and work in new areas. ODM Aviation will add new transportation capabilities to a city bypassing geographic barriers and providing accessibility to new regions. This may evolve city structure and create a variety of positive and negative externalities.  |

These potential benefits are considered positive externalities of ODM Aviation and many of them shall be discussed further throughout this thesis. While the aviation community has tended to focus on these benefits, a variety of potential negative impacts of ODM Aviation are also identified in this thesis. These include factors such as increased community noise and pollution, reduced safety

for bystanders on the ground, privacy concerns, a hollowing of the urban core, a reduction of demand for public transportation and the further separation of the economic classes, among others.

The purpose of this thesis is to assess the operational potential of ODM Aviation. Research questions one and two of this thesis specifically motivate the identification of additional challenges and externalities that may result from ODM Aviation implementation and operation. Substantial portions of this thesis will discuss the challenges facing ODM Aviation and review possible mitigations.

### 2.2.3 A Preponderance of Terms

While this thesis has chosen to use “On Demand Mobility for Aviation” to describe providing on demand, aircraft-based transportation services in metropolitan areas, the literature and industry have put forward dozens of terms to describe this service and related concepts. To clarify the difference between various proposals for aircraft-based transportation modes in urban areas, an effort was made to document and relate the various terminology.

#### 2.2.3.1 Terminology for Aircraft-Based Transportation in Metropolitan Areas

As introduced in Section 2.1, aircraft-based urban mobility has a long history of development and previous implementation attempts. Whether a result of each new attempt trying to distinguish itself from previous efforts, or a desire to better capture the essence of the service and technology, a preponderance of terms have been proposed that all describe similar notions of metropolitan aircraft-based transportation. Table 4 presents a documentation of major terms that have been proposed to describe the field. Most have fallen out of favor and common use, however it is informative to consider these terms to identify previous research and progress in the field as well as scrutinize the appropriateness of today’s favored term.

Table 4. History of terminology for aircraft-based transportation in metropolitan areas.

| <b>Term</b>                              | <b>Usage Dates</b> | <b>Referenced By</b> |
|--|--------------------|----------------------|
| Helicopter Air Carrier                   | 1953 - 1976        | [19], [20]           |
| Air Taxi                                 | 1962 - 2016        | [19], [20], [23]     |
| Metrotaxi/Metrobus                       | 1970               | [20]                 |
| Intracity Air Transportation             | 1970               | [20]                 |
| Interurban Short Haul Air Transportation | 1973               | [22]                 |
| Personal Air Transportation              | 2006               | [38]                 |
| On Demand Aviation                       | 2010 - 2015        | [53], [55]–[57]      |
| On Demand Air Mobility                   | 2012               | [10]                 |
| Zip Aviation                             | 2012 - 2014        | [12], [58]           |
| Sky Transit                              | 2015 - 2016        | [59], [60]           |
| On Demand Mobility                       | 2015 - 2016        | [13], [61]           |
| Air Mobility on Demand                   | 2016               | [52]                 |
| On Demand Urban Air Transportation       | 2016               | [2]                  |
| Urban Air Mobility                       | 2016               | [62]                 |

The coordinating organization for the aircraft-based mobility community has been NASA. Through a variety of workshops beginning in Oshkosh, WI in July 2015, NASA brought together

manufacturers, researchers and potential operators to conduct pre-competitive studies and standards definition to support the development of the industry. Considering the convergence of the relevant stakeholders at these working groups and through the NASA program, this research chose to adopt the preferred NASA term of “On Demand Mobility”. However, seeing as ODM has far greater association with the more well developed ground transportation modes and operators, and in reality describes transportation agnostic of the vehicle type, the specification of “aviation” was appended by the author; thus, On Demand Mobility for Aviation. As a side note, the author personally believes the term “On Demand Air Mobility” most succinctly describes the industry and service.

### 2.2.3.2 A Hierarchy of Transportation Modes

Beyond the aviation industry, ODM networks have already achieved substantial proliferation in automobile transportation as discussed in Section 2.2.1. It is a useful exercise to consider the relation of ODM Aviation to these other forms of transportation and note relations between the terminology used in each domain. Figure 7 presents a notional hierarchy of the relevant transportation terminology.

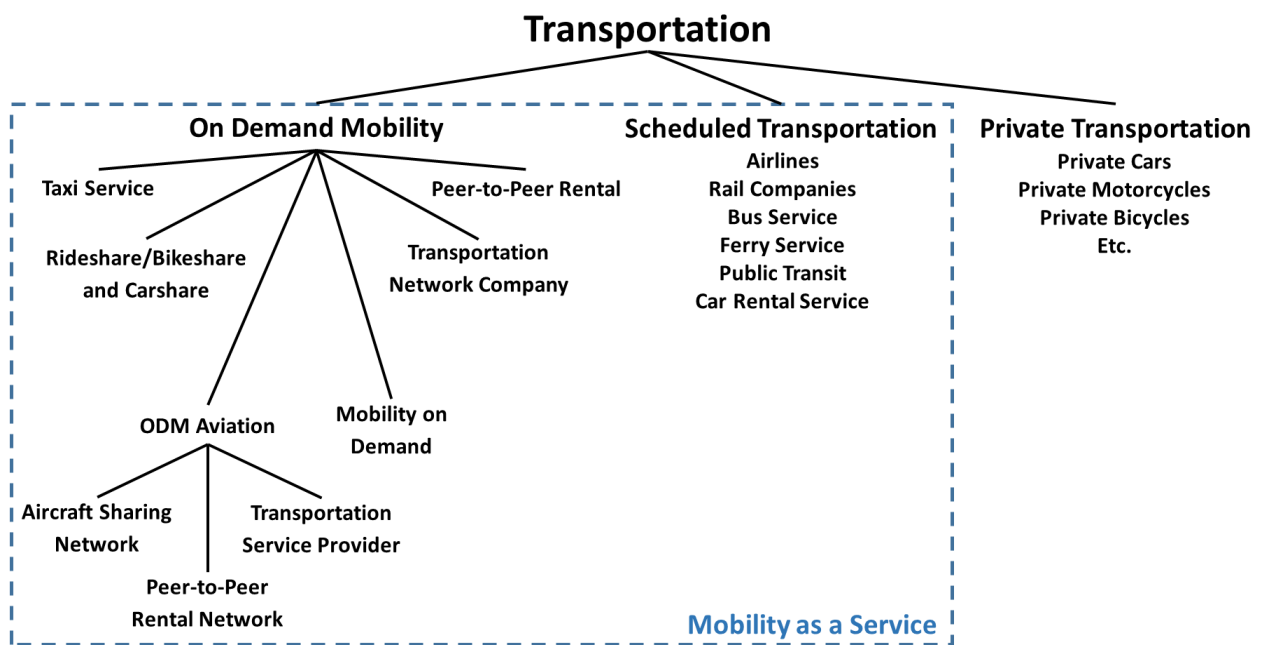


Figure 7. Hierarchy of transportation modes displaying relevant terminology from the literature.

Although often mistaken for a semantic difference in the literature, there is actually a material difference between the concepts of “on demand mobility” and “mobility on demand.” Mobility on Demand (MoD) was proposed and developed as a concept nearly entirely within the MIT Media Lab and specifically refers to the use of specially designed electric vehicles distributed throughout a geographic area that are either driven by the customer or autonomously controlled [51]. Future ODM Aviation networks using autonomous electric vehicles are likely to be considered MoD. The MoD community has made significant progress in many of the demand management and route planning algorithms for vehicle networks.

### ***2.3 Enabling Technologies for ODM Aviation***

While various forms of ODM Aviation and personal air mobility have been attempted over the past century, authors and entrepreneurs point to the recent emergence of a few advanced technologies they believe are breakthroughs that will enable profitable, aircraft-based metropolitan transportation. Pervasive telecommunications networks, electric propulsion and automation are the three primary technologies that are believed will revolutionize both ground and air transportation. These technologies have by and large been developed in industries other than aviation. Proponents of ODM Aviation therefore suggest that the convergence of these technologies with aircraft design and operation will address the critical challenges earlier developers faced [11], [12], [53], [63], [64].

A 1970 study of intracity air transportation systems by the MIT Flight Transportation Laboratory [20] identified four key R&D areas that must be addressed to allow for the successful implementation of urban air systems:

- 1) “Research and development of quiet rotor vehicles”
- 2) “Development of auto-stabilized VTOL vehicles”
- 3) “Development of new automated ATC systems”
- 4) “Development of computerized passenger processing systems”

Then, beginning in 1999, the Small Aircraft Transportation System was developed to address vehicle, airspace and air traffic control challenges facing inter-urban air taxi services. This program identified two additional areas that must be addressed to allow for the successful implementation of urban air systems [65], [66]:

- 5) Development of higher volume operations for IFR conditions at small airports
- 6) Develop a new generation of affordable, small, high-performance aircraft to make use of community airports

While new technologies often bring about new interest and investment in a market, such as was seen in the VLJ market in the early 2000’s and again in the ODM Aviation markets today, challenges that are not addressed by the new technology may be ignored or go unrecognized. Considering this, emergent capabilities in electric propulsion, telecommunications and automation may address challenges 1, 2, 4 and 6 identified by these two studies, but they will not address the two challenges related to ATC. Although the ATC challenge has been known since 1970, there has been little focus in the current ODM Aviation community to address it. One of the purposes of this thesis was to identify constraints that limit the operational potential of ODM Aviation, particularly those that may not be addressed by emerging technologies, and bring them into focus for the ODM Aviation community.

An overview of the potential application of electric propulsion, telecommunications and automation in ODM Aviation is provided below. The specific ODM Aviation constraints that may be addressed by the new technologies are discussed.



### **2.3.1 Electric Aircraft Performance Overview**

Proponents of ODM Aviation suggest that more-electric aircraft are a fundamental enabling technology that overcome many of the challenges that plague helicopter and small aircraft air taxi services. The reduced power to weight ratio, increased overall efficiency and beneficial airframe integration opportunities of electric propulsion are anticipated to result in electric aircraft performance that is superior to conventionally powered aircraft for short range missions [1]. Furthermore, distributed electric propulsion technologies are also proposed to reduce the noise profile of aircraft and mitigate community acceptance challenges. Finally, it is hypothesized that full-electric aircraft may lead to as much as a 20% reduction in direct operating costs as compared to conventional aircraft primarily due to increased overall efficiency and reduced maintenance costs [67].

As with many potentially disruptive technologies, electric propulsion technologies are rapidly evolving and capabilities are not well understood. Therefore, to inform the development of the case study the author deemed it appropriate to evaluate the likely performance capabilities and operational costs of near-term electric aircraft through a first principles analysis. These capabilities and costs were compared to those of a conventional aircraft to determine if there was a mission profile for which electric aircraft were superior.

The comparative study, included within this section of the thesis background, suggested that full-electric aircraft were able to meet the performance needs of ODM Aviation missions up to 100 miles in range while maintaining takeoff weights comparable to conventional aircraft. For these missions, the electric aircraft required over 70% less on-board energy and reduced total fuel/energy costs by 83% compared to the conventional aircraft using 100 low lead (LL) Avgas.

The utilization of electricity as an alternative or complementary propulsion source for aircraft is not a novel idea. The first electrical propulsion systems for aircraft were proposed as early as 1943 and sought to capture benefits of distributed propellers and electrical motors [68]. Between 1983 and 2003 NASA partnered with AeroVironment to produce and fly four flight test vehicles to advance the fundamental technologies of full-electric solar flight. Through the Pathfinder, Pathfinder-Plus, Centurion and Helios unmanned systems NASA refined electric drive and distributed electric propulsion concepts [69].

Simultaneously to these public developments, numerous private companies explored man-rated vehicles whose performance increased proportional to the incrementally improving energy density of batteries and fuel cells. These developments were featured in the 2011 Green Flight Challenge where multiple, prototype, full-electric aircraft flew a 200 mile mission in two hours using less than the energy equivalent of a gallon of fuel per passenger. A variety of companies now intend to produce full-electric general aviation (GA) aircraft in the next decade. Perhaps epitomizing the progress made in the field to date, the Swiss aircraft Solar Impulse just completed the first circumnavigation of the globe by a full-electric vehicle.

Beyond these aerospace specific developments, advancements in electric engine power density and energy storage (battery) technologies have primarily been driven by the automotive and heavy industry sectors. Hybrid and full-electric car production is many orders of magnitude larger than electric aviation is projected to be, and therefore the substantial resources of this industry are likely to continue driving forward the state of this technology.

However, notwithstanding the advancements that have been made in manned solar vehicles and high altitude, long duration solar UAS, cost effective full-electric regional or long-haul commercial aircraft are not likely to be viable in the near future due to insufficient energy storage capabilities [70]. Despite this limitation at the large end of the passenger and payload spectrum, electric propulsion, integration and storage technologies have advanced to the point to potentially support economically viable short range aircraft suitable for ODM Aviation.

### 2.3.1.1 First Order Aircraft Performance Model

The Breguet range equation is a first order performance model for fixed-wing aircraft in steady level flight. Although the equation neglects multiple factors relevant to the actual ConOps of ODM aircraft, such as fuel expended while climbing and descending or wind impacts, the equation is useful to conduct early phase performance studies and compare conventional and electric aircraft. Equation (2.1) presents the Breguet range equation for a conventional piston powered propeller driven aircraft [71].

$$R = \frac{\eta_{pr}}{C} * \left(\frac{L}{D}\right) \ln\left(\frac{W_i}{W_f}\right) \quad (2.1)$$

In Equation (2.1), “R” is the range of the aircraft during cruise, “ $\eta_{pr}$ ” is the propeller efficiency, “C” is the specific fuel consumption, “L/D” is the lift to drag ration, “ $W_i$ ” is the initial weight of the vehicle at the start of cruise and “ $W_f$ ” is the final weight of the vehicle at the end of cruise.

In electric aircraft energy is extracted from batteries rather than through the combustion of fuel. Since battery weight does not change in proportion to energy extraction, the traditional Breguet range equation is not applicable except for short ranges. Therefore, Equation (2.2) presents an alternative range equation for full-electric aircraft as derived by Martin Hepperle [72].

$$R = \frac{E' * \eta_o}{g} * \left(\frac{L}{D}\right) \left(\frac{m_{batt}}{m_o}\right) \quad (2.2)$$

In Equation (2.2), “E” is the mass specific energy content of the batteries (or other energy storage device), “g” is gravitational acceleration, “ $\eta_o$ ” is the overall electric propulsion system efficiency, “ $m_{batt}$ ” is the mass of the batteries and “ $m_o$ ” is the total mass of the aircraft. Unlike the fuel mass fraction in the conventional Breguet range equation, the battery mass fraction in Equation (2.2) does not appear inside a natural logarithm because the battery weight is constant and the aircraft does not become lighter through flight. It should be noted that while this analysis assumed Lithium-Ion battery chemistries that maintain a static weight, some forthcoming batteries (such as Lithium-Oxygen) actually *gain* weight as they are discharged.

### 2.3.1.2 Comparison of Electric and Conventional Aircraft Performance

This brief study characterized the range, energy usage and fuel/energy cost of conventionally and electrically powered aircraft. By selecting values for the parameters on the right hand side of Equations (2.1) and (2.2) that represent the current state of the art in aircraft manufacturing and electric propulsion, it was possible to approximate reasonable capabilities for both types of vehicles as of 2016.

ODM operations will likely use relatively new helicopter, fixed-wing and tilt-rotor aircraft. This initial performance study focused only on fixed-wing vehicles due to the simplicity of range and energy usage evaluation through the Breguet range performance model. Near-term regulations and autonomy technologies require all commercial operations to have at least one pilot. Therefore it is probable that a viable aircraft for commuter or point-to-point ODM operations will have capacity for 1 to 4 passengers plus a pilot.

Considering these factors, the Cirrus SR22 was selected as a representative conventionally powered aircraft that may potentially be used for ODM operations. The SR22 is a four passenger, composite aircraft commonly flown by GA pilots. The comfortable interior, relatively high cruise speed and emergency recovery parachute system make it an attractive choice as a fixed-wing ODM aircraft. Table 5 highlights key parameters of the SR22.

Table 5. Cirrus SR22 specifications.

| Parameter                           | Unit     | Value    | Source     |
|-------------------------------------|----------|----------|------------|
| Max Takeoff Weight                  | lbs      | 3600     | [73]       |
| Empty Weight                        | lbs      | 2260     | [73]       |
| Useful Load                         | lbs      | 1340     | [73]       |
| Max Payload (full fuel/max allowed) | lbs      | 788/1140 | [73]       |
| Usable Fuel Load                    | gal/lbs  | 92/552   | [73]       |
| Engine Dry Weight                   | lbs      | 412      | [74]       |
| Engine Horsepower                   | hp       | 310      | [74]       |
| Propeller Efficiency                | ~        | 0.85     | assumption |
| Specific Fuel Consumption           | lb/hp*hr | 0.45     | assumption |
| Cruise Lift to Drag Ratio           | ~        | 11       | [75]       |
| Maximum Range                       | nm       | 811      | [73]       |
| Cruise Speed 75% Power              | ktas     | 184      | [73]       |

Due to the rapidly changing nature of the electric aircraft technologies, this study developed a notational electric vehicle using technologies comparable to those in the SR22. This allowed for a direct comparison of the impacts of transition from a conventional propulsion system to an electric system.

To determine notional electric aircraft structural weight as a function of the maximum takeoff weight, a parametric weight relation developed by Jan Roskam for single engine propeller driven aircraft was used; the original relation is displayed in Figure 8 [76]. The weight relation slightly under predicted the empty weight of the SR22, perhaps due to its high performance engine and avionics.

To modify the relation to provide aircraft structural weight rather than empty weight, the SR22 structural weight (empty weight minus engine weight) was compared to the historical data and found to be 218 lbs below the trend line. This off-set factor was applied as a linear coefficient to Roskam’s original weight relation. Equation (2.3) expresses the adjusted function that provided aircraft structural weight as a function of maximum takeoff weight.

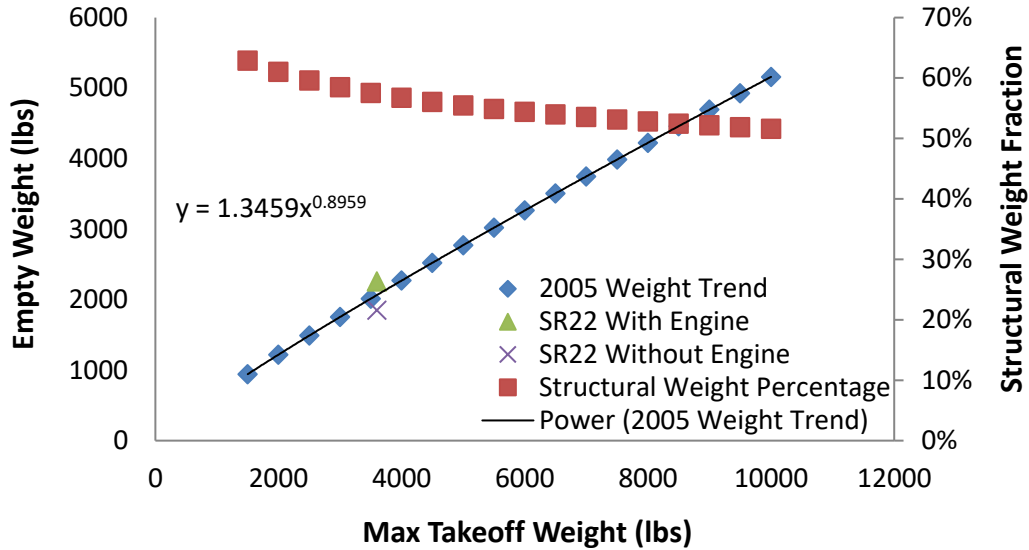


Figure 8. Weight trend for single engine propeller driven airplane with SR22 indicated.

$$W_{structure} = 1.3459 * W_{MTO}^{0.8959} - 218 \quad (2.3)$$

Next, information was collected about the state of the art aerodynamic, energy storage and distributed electric propulsion (DEP) technologies; Table 6 displays these values. Please note that the general performance requirements for the full-electric aircraft, such as maximum payload, were chosen to match the SR22 to allow for an effective comparison between the two vehicles.

Table 6. Notional full-electric aircraft specifications based on current technology.

| Parameter                    | Unit    | Value | Source |
|------------------------------|---------|-------|--------|
| Mass Specific Energy Content | W*hr/kg | 200   | [75]   |
| Cruise Lift to Drag Ratio    | ~       | 17    | [75]   |
| Overall Efficiency           | ~       | 0.73  | [72]   |
| Engine Power Density         | hp/lb   | 4.5   | [77]   |
| Max Payload                  | lb      | 1140  | [73]   |
| Cruise Speed 75% Power       | kts     | 174   | [75]   |

The parameter values presented for the conventionally powered and full-electric aircraft were applied to the Bruguet range performance model with a given mission range requirement to back out the takeoff weight of each aircraft. The energy required by each vehicle to fly the mission was then determined by subtracting the structural, propulsion system and crew/cargo weights from the determined takeoff weight to find the remaining fuel or battery weight requirements. These weights were converted to energy requirements through the energy content of avgas or the energy density of the batteries, respectively.

As a note, while the SR22 was permitted to only carry the fuel required for the mission range commanded, the electric aircraft was required to carry a full complement of batteries for each flight no matter the range. This assumption was intended to capture the relatively permanent nature of

batteries in electric aircraft. Battery mass above and beyond that needed for fly the mission was considered as payload and was not considered as providing energy necessary to complete the mission. No reserve fuel (or electrical energy) was considered for this initial analysis, although Federal Aviation Regulations (FARs) require such reserves and fully discharging batteries may reduce their useful cycle life.

Figure 9 displays the energy requirements for each aircraft. The full-electric aircraft was found to consume less energy for missions under 225 miles in range than the conventionally propelled aircraft. For trips up to 100 miles in range, this analysis suggested electric aircraft may require as much as 76% less on-board energy than conventional aircraft. These results are consistent with those found by NASA research [1], [12].

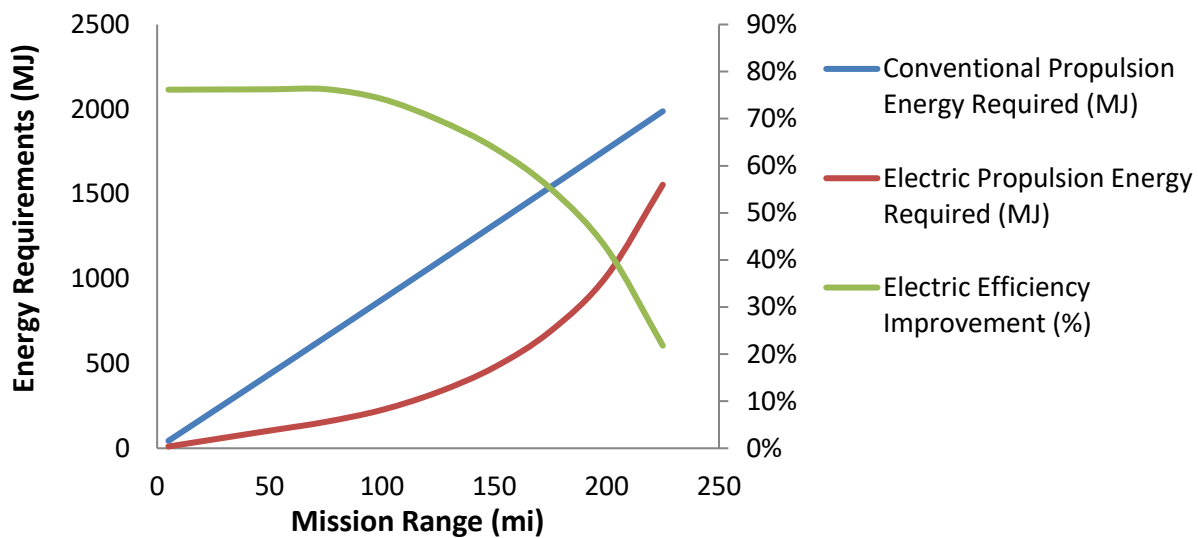


Figure 9. Comparison of energy requirements between full-electric and piston engine aircraft.

The U.S. Energy Information Administration found the national average price of electricity in 2015 to be ¢10.64 per kWh for commercial customers, ¢6.91 for industrial customers, and ¢10.09 for transportation customers [78]. While these prices vary dramatically from state to state and month to month, it was assumed that the energy cost for the full-electric aircraft was the national average (across all sectors) of ¢10.41 per kWh, or ¢2.89 per MJ. The U.S. national average price of 100LL aviation fuel in November and December of 2016 was \$4.71 per gallon [79]. This equates to a conventional fuel cost of ¢3.94 per MJ. Therefore, for missions of 100 miles or less, the energy costs for a full-electric aircraft may as great as ~83% lower than the fuel costs for a conventional aircraft.

The dramatic reduction in on-board energy usage (and resulting reduction in costs) predicted for full-electric aircraft for these short range missions is primarily the result of the much higher conversion efficiency of battery-stored electrical energy to useful work than the useful work extracted from hydrocarbon fuel in internal combustion engines (ICEs). Figure 10 displays overall efficiencies for typical aircraft propulsion architectures. While internal combustion engines convert only ~25% of the energy content of the fuel to useful work, releasing the rest as heat, electric aircraft may convert over 75% of energy stored in batteries to useful work.

It should be noted that on-board energy consumption was defined for conventional aircraft as the total energy content contained within the fuel burned during the mission. For full-electric aircraft, the on-board energy consumption was the total electricity drawn from the batteries for the mission. Energy consumption for either vehicles did not include a full “well-to-wake” analysis. Such an analysis is useful to support an environmental impact comparison of full-electric and conventional aircraft propulsion. The total well-to-wake efficiency of electric aircraft depends upon how electricity is produced (renewables versus fossil fuel generation) and distributed and is discussed in greater detail in Section 2.3.1.3.

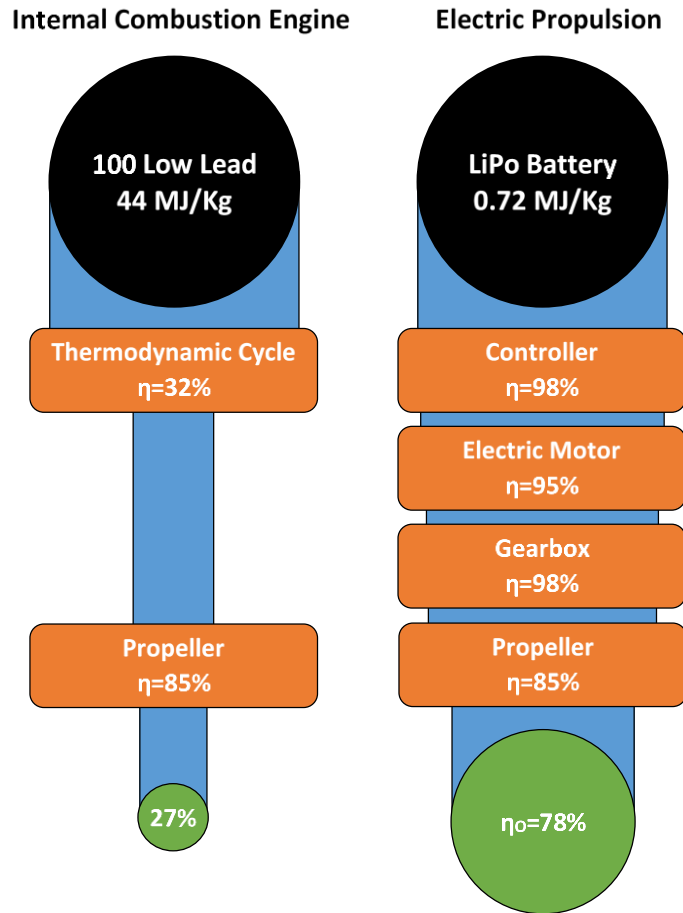


Figure 10. Comparison of the overall efficiency of a conventionally powered SR-22 with the proposed overall efficiency of a full-electric propulsion variant. *Image based upon research by Martin Hepperle [72].*

The second primary factor contributing to the predicted energy usage reduction of full-electric aircraft was the given increase in cruise lift to drag ration (L/D). While the SR-22 had a cruise L/D of 11, the full-electric aircraft with distributed electric propulsion was anticipated to have a cruise L/D of 17. This increase in L/D is possible in full-electric aircraft because the distribution of small electric propulsors over the wing creates a “blown wing” that allows the aircraft to fly at higher angles of attack during takeoff and landing without stalling the wing. The higher possible lift coefficient enables aircraft designers to reduce the wing area and therefore increase L/D during cruise while maintaining sufficient takeoff and landing performance.

While the predicted 76% energy efficiency improvement of full-electric propulsion may appear unreasonable, the alternative form of the Breguet range equation provided in Equation (2.4) may be used to derive this efficiency increase mathematically from the increase in aircraft L/D and overall efficiency. Equation (2.4) is valid for conventionally powered propeller-driven aircraft where  $h_c$  is the fuel energy per unit mass (lower heating value).

$$R = \frac{h_c}{g} * \eta_o * \left(\frac{L}{D}\right) \ln\left(\frac{W_i}{W_f}\right) \quad (2.4)$$

The range of an aircraft is directly proportional to the energy required for the flight. If two aircraft are provided with the same initial amount of energy (fuel), then an increase in range of one aircraft over the other represents an equivalent increase in energy efficiency of that aircraft. Therefore, Equation (2.5) displays an equation for the efficiency improvement of two conventionally powered propeller-driven aircraft that are assumed only to differ in their lift to drag ratio and overall efficiency:

$$\text{Efficiency Improvement} = 1 - \frac{R_1}{R_2} = 1 - \frac{\frac{h_c}{g} * \eta_{o1} * \left(\frac{L}{D}\right)_1 \ln\left(\frac{W_i}{W_f}\right)}{\frac{h_c}{g} * \eta_{o2} * \left(\frac{L}{D}\right)_2 \ln\left(\frac{W_i}{W_f}\right)} = 1 - \frac{\eta_{o1} * \left(\frac{L}{D}\right)_1}{\eta_{o2} * \left(\frac{L}{D}\right)_2} \quad (2.5)$$

The overall efficiency and L/D for the full-electric aircraft may be entered in the numerator of Equation (2.5), and the characteristics of the conventionally propelled SR22 in the denominator. As can be seen in Equation (2.6), the resultant aircraft energy efficiency improvement is 76%, or what was predicted in Figure 9. The anticipated increase in overall efficiency from a change to electric population equates to a 63% energy usage reduction on its own, while the increase in cruise L/D from 11 to 17 results in a 35% usage energy reduction on its own. Taken together, the higher L/D and overall efficiency create the potential for a 76% overall energy usage reduction.

$$\text{Efficiency Improvement} = 1 - \frac{\eta_{o1} * \left(\frac{L}{D}\right)_1}{\eta_{o2} * \left(\frac{L}{D}\right)_2} = 1 - \frac{0.73 * 17}{0.27 * 11} = 0.76 = 76\% \quad (2.6)$$

While these equations were only valid for conventionally-powered, propeller-driven aircraft, they approximate the performance of electric aircraft for short range missions. As seen in Figure 11, electric aircraft are expected to maintain maximum takeoff weight parity with the conventional aircraft for mission ranges up to 75 miles. The SR22 burns 33 lbs of fuel for a 75 mile mission, or 1% of its takeoff weight. A 1% reduction fuel weight over the course of the flight corresponds to a range increase (or energy usage reduction) of approximately 1% for conventional aircraft compared to full-electric aircraft. The difference due to fuel burn is therefore negligible compared to the large reductions that result from changes in L/D and overall efficiency, and therefore the exercise conducted for two conventionally powered aircraft in Equation (2.6) is also valid for an electric aircraft.

The energy efficiency improvement of electric aircraft was seen in Figure 9 to rapidly decay for mission ranges of greater than 100 miles. The degrading performance was a direct result of the

comparatively low energy density of batteries and the dramatic growth in aircraft weight that was required to achieve mission ranges greater than 100 miles. The overall takeoff weight for a conventional aircraft increases only as a result of the additional fuel necessary to fly the additional mission range. Even for the maximum mission range considered in this analysis (225 miles), the fuel weight required was only 100 lbs, well under the 552 lb capacity of the SR-22. This trend holds true until the maximum takeoff weight of the aircraft is reached at which point payload must be substituted for the necessary additional fuel.

The specific energy density of current batteries is much lower than that of hydrocarbon fuels and results in a dramatically different aircraft weight trend, however. Figure 11 displays the weight buildup for the full-electric aircraft as a function of mission range. The energy consumption of the vehicles is also provided as a secondary horizontal axis. The figure displays that full-electric aircraft have an inflection point in mission range where the takeoff weight of the aircraft increases dramatically with increasing range. For the performance and energy storage estimations made in this study, the inflection point appears to be roughly 100 miles in range. For missions less than 100 miles, a full-electric aircraft can carry the same payload as a conventional aircraft at the same maximum takeoff weight. However, for missions greater than 100 miles, the low energy density of battery technologies compared to hydrocarbon fuel results in the dramatic increase in battery weight and aircraft structural weight for each additional mile of range of the full-electric aircraft compared to the conventional aircraft.

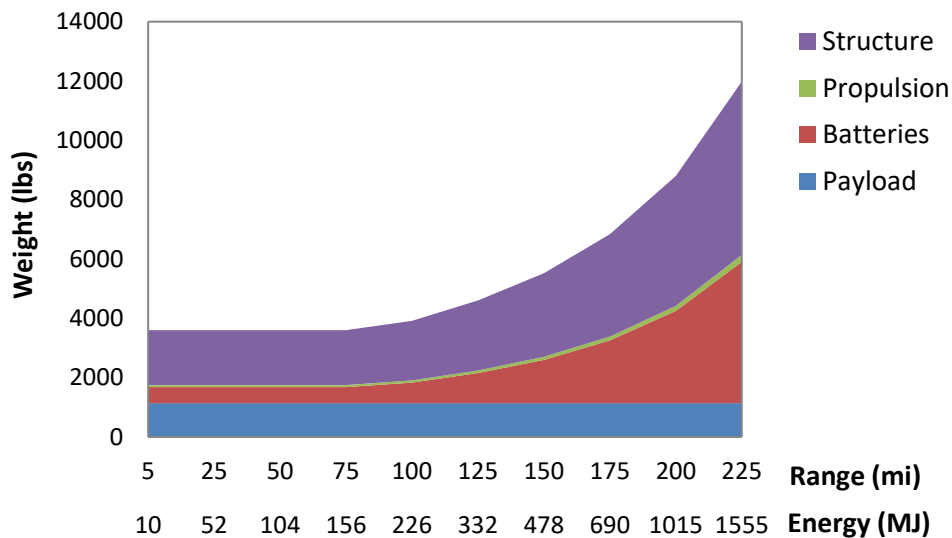


Figure 11. Full-electric aircraft weight fractions and energy requirements for missions of increasing range.

### 2.3.1.3 First Order Comparative CO<sub>2</sub> Lifecycle Assessment of Full-Electric ODM Aircraft

While the previous section displayed how full-electric aircraft may substantially reduce in-flight energy consumption compared to conventional aircraft, a lifecycle assessment is necessary to assess if the “cradle to grave” environmental impact of electric aircraft is also superior to that of conventional aircraft. To account for the lifecycle environmental impacts of ODM aircraft operation, three additional factors beyond in-flight energy consumption were considered. These



factors were electricity production and distribution, aircraft useful life, and aircraft construction and disposal.

The primary anticipated difference (from an environmental standpoint) for the manufacturing and disposal of electric and conventional aircraft is the battery assembly, electric engines and power distribution hardware. According to a 2013 EPA lifecycle analyses of transportation-grade lithium-ion batteries for use in electric vehicles, the production and recycling of large-capacity batteries creates negative impacts for global warming, environmental pollution, rare-earth metal depletion and human health [80]. However, a study by the Swiss Federal Laboratories found that the additional environmental impacts from battery production, use and disposal were insignificant when compared to the environmental burdens generated during the lifespan of vehicle operation [81]. Furthermore, this study also suggested that the environmental impacts of battery replacement are insignificant compared to the impacts generated during the lifespan of vehicle operation as well. Considering these factors, differences in the environmental burdens resulting from differences in electric aircraft and conventional aircraft useful life, construction and disposal were considered negligible for the lifecycle assessment.

Figure 9 displayed a first order, in-flight energy usage comparison of electric and conventional aircraft. This initial analysis was supplemented to capture the environmental impacts associated with battery charging, electricity distribution and electricity production. A battery charging efficiency factor of 90% was assumed to represent the loss of 10% of the supplied electrical energy through heat dissipation during fast charging processes [67]. Similarly, an efficiency factor of 95.05% was applied to electricity distribution from the generation source to the aircraft charger based upon the 4.95% average energy loss of the U.S. electric grid as reported by the U.S. EPA in 2014 [82].

It was found that the environmental impact of electric aircraft is critically dependent upon the power generation resource mix for the electric grid from which the ODM aircraft draws charge. At one extreme, if an ODM aircraft only drew charge from a fully renewable generation source (solar, wind, hydroelectric, etc.) then the environmental impacts of generating electricity for that flight may be nearly negligible corresponding only to land use change, watershed degradation, hazard to wildlife, and other second order impacts. At the other extreme, however, electricity generation through primarily fossil fuel sources may present a host of environmental impacts including GHG emissions, human health impacts from particulate matter, or damages from resource extraction, for example.

Based upon this consideration, the environmental impacts of ODM Aviation may vary dramatically from region to region depending upon the power generation portfolio of that area. Figure 12 displays the power generation portfolios of the 50 states and their resultant CO<sub>2</sub> emissions rate per MWh of electricity. Table 7 presents representative electrical generation total output emission rates for electrical grid subregions in the U.S. as reported by the U.S. EPA.

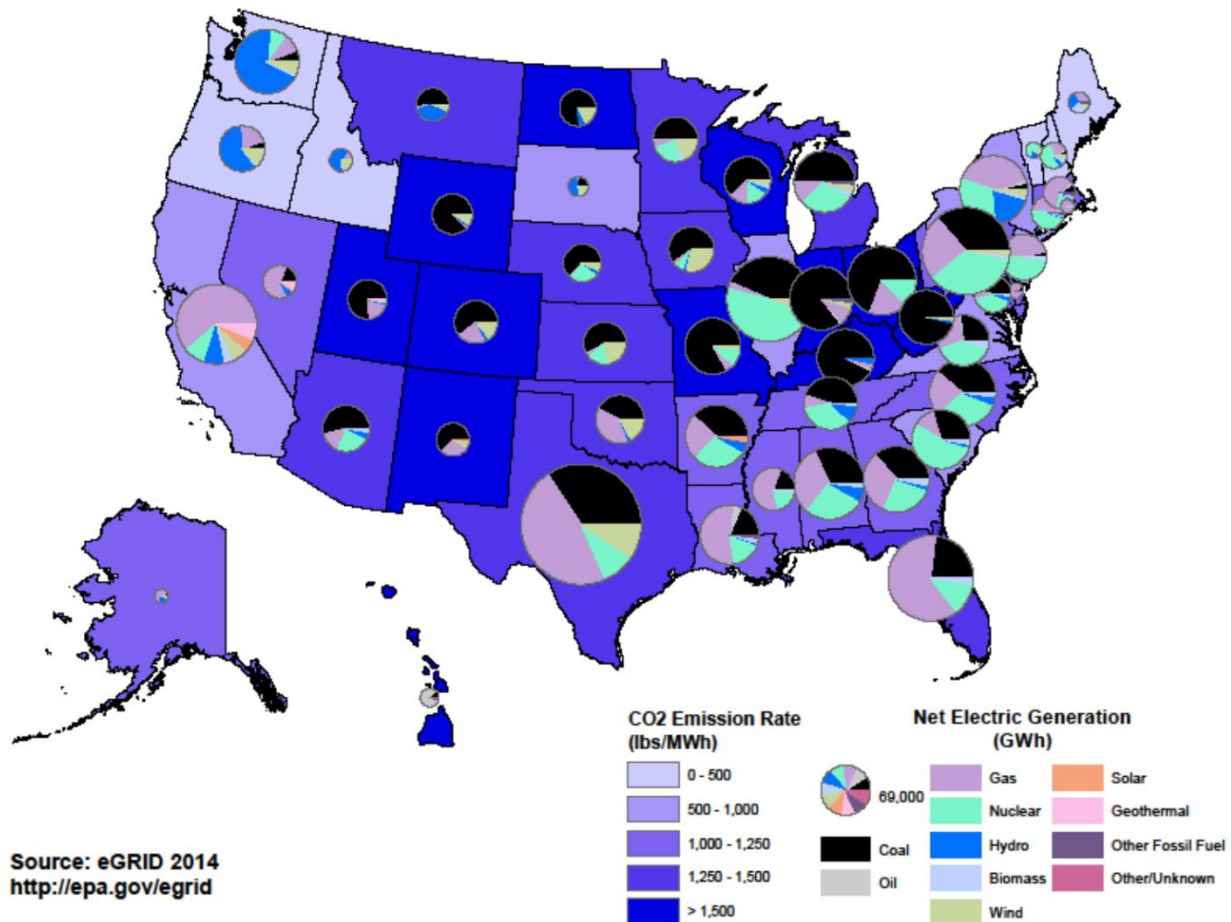


Figure 12. Average electricity generation resource mix and CO<sub>2</sub> emissions rate for the U.S.  
 Image reprinted from EPA eGRID 2014 available at <http://epa.gov/egrid> [82, p. 13].

Table 7. 2014 greenhouse gas emissions for representative U.S. subregions. Data retrieved from U.S. EPA eGRID available at <http://epa.gov/egrid> [82, p. 2].

| Subregion     | Carbon Dioxide (CO <sub>2</sub> )<br>lb/MWh | Methane (CH <sub>4</sub> )<br>lb/GWh | Nitrous Oxide (N <sub>2</sub> O)<br>lb/GWh | CO <sub>2</sub> Equivalent (CO <sub>2</sub> e)<br>lb/MWh |
|---------------|---|--------------------------------------|--|--|
| U.S. Average  | 1,143.0                                     | 112.3                                | 16.2                                       | 1,150.3  |
| U.S. Cleanest | 377.2                                       | 32.3                                 | 4.4  | 379.2  |
| U.S. Dirtiest | 1,774.0                                     | 185.3                                | 26.8                                       | 1,786.2  |
| California    | 619.9                                       | 36.7                                 | 4.5  | 621.9  |

The functional unit chosen for the lifecycle assessment was one statute mile flown by an aircraft. The resultant unit of environmental impact was therefore gCO<sub>2</sub> per mile. While the actual environmental impacts of CO<sub>2</sub> emissions by centralized power plants and distributed conventional aircraft are different (due to dispersion patterns, emissions at altitude and local area impacts, among others), these difference were neglected in this first order analysis.

CO<sub>2</sub> emissions were chosen in this analysis as the unit of environmental impact, rather than CO<sub>2</sub> equivalent or other metrics such as human health because the emissions of CO<sub>2</sub> from internal combustion engines in automobiles and conventional aircraft is fairly consistent on a per gallon of fuel basis. Impacts and emissions of other GHGs vary significantly based upon conditions and vehicles and are therefore more difficult to capture. Furthermore, CO<sub>2</sub> is the GHG with the most significant total climate impact (not per unit, but due to the large quantity emitted) and is therefore an appropriate indicator for the environmental impact difference between electric and conventionally powered aircraft.

Based upon these assumptions, and noting that 1 MJ = 0.278 KWh, CO<sub>2</sub> emissions from generation and distribution were added to the data from Figure 9. Emissions for conventional aircraft were assumed to be 18.355 lbs of CO<sub>2</sub> per gallon of 100 LL fuel consumed. Furthermore, additional emissions related to the extraction, processing and transportation of 100LL fuel or fuels for electricity generation were not considered. Although these additional emissions sources are important for a full cradle to grave lifecycle assessment, they were not deemed necessary for the comparative assessment at hand.

Figure 13 displays the results of the comparative assessment between CO<sub>2</sub> emissions from conventionally powered and electrically powered aircraft. The significant influence of the resource mix of the electricity generation portfolio is notable. If the electricity for ODM Aviation is generated primarily from coal and other fossil fuels, as is the case for the dirtiest generation curve, then the CO<sub>2</sub> emissions from conventional and electrically powered aircraft are nearly indistinguishable for short range missions, and significantly worse for electric aircraft on longer missions. With this resource mix, other less significant environmental impact factors including battery development and disposal may no longer be negligible and may result in a worse environmental impact for electric aircraft than conventionally powered aircraft.

However, CO<sub>2</sub> emissions from electric aircraft are roughly cut in half if the average U.S. energy generation resource mix is considered. Furthermore, utilizing the cleanest U.S. resource mix or the California resource mix (with their higher degree of nuclear or renewable sources) provides significant CO<sub>2</sub> reductions up to 81% and 69% compared to conventionally powered aircraft, respectively.

The first order analysis conducted in this section indicates that for regions of the country with average or relatively clean electricity production resource mixes, the transition from conventional piston-driven aircraft to electric aircraft will provide significant emission reductions and result in a reduction of the associated negative externalities from pollution.

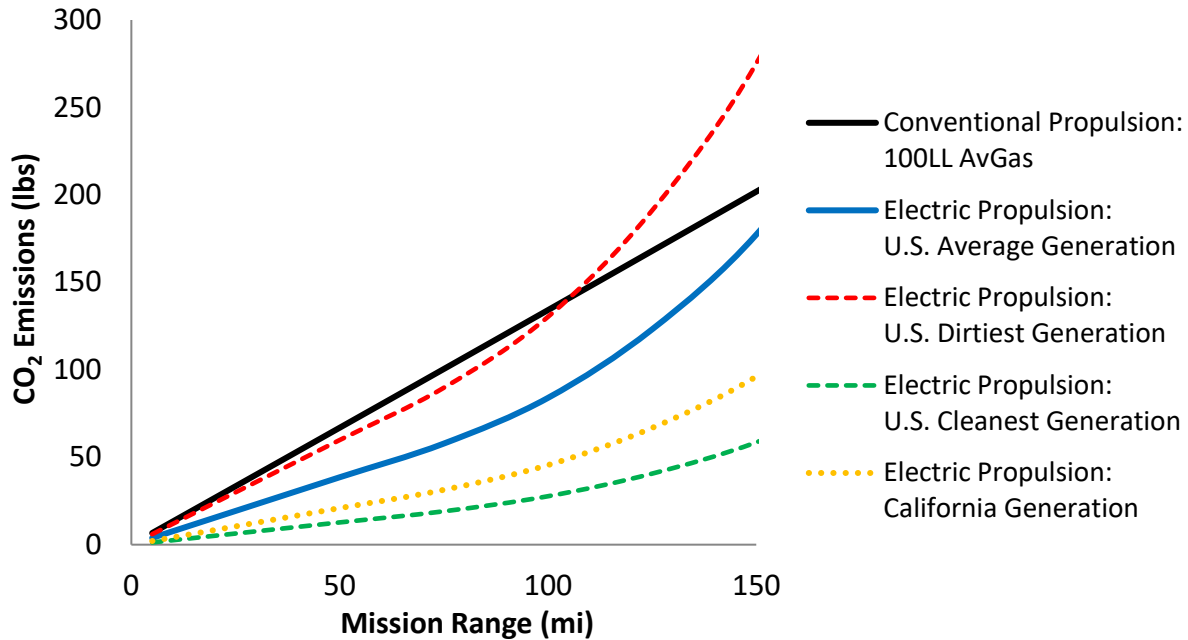


Figure 13. Comparison of CO<sub>2</sub> emissions for conventionally powered and electrically powered aircraft displaying the influence of the cleanliness of the electricity generation resource mix.

#### 2.3.1.4 Discussion of Electric and Conventional Aircraft Operating Economics

It was shown in Section 2.3.1.2 that electric aircraft with current technologies may have performance advantages over conventionally powered aircraft for missions with ranges up to roughly 100 miles. These performance advantages degrade for missions with ranges of over 100 miles due to the large mass of batteries that must be carried as a result of the low energy density of current battery technologies. However, even for missions with a range of 200 miles, Figure 9 indicated that full-electric aircraft may expend less total on-board energy than conventionally powered aircraft.

While takeoff weight and energy usage are key aircraft performance attributes, the ultimate competitiveness of full-electric aircraft in the market will depend upon the operating economics of these vehicles. Put simply, full-electric aircraft may be adopted for routes and missions where their direct operating cost is equivalent to or less than that of conventionally powered competitor aircraft, assuming the performance of the electric vehicle is comparable for attributes key to airline operation.

Direct operating costs are costs that are incurred by an airline as a result of the actual flight of an aircraft. For ODM aircraft operation, direct operating costs were assumed to include pilot wages, energy costs, maintenance costs and the costs of aircraft ownership. Crew costs, although typically considered a direct operating cost, were not considered for ODM operators as the small aircraft anticipated for these missions would not have on-board personnel except for the pilot. Furthermore, it was assumed that maintenance costs of electric aircraft included the costs of battery replacement in addition to the traditional costs of engine, avionics and propeller overhaul, among other maintenance requirements. Finally, aircraft ownership costs were assumed to include financing, depreciation and insurance for the aircraft.

To identify if and how full-electric aircraft may reduce an ODM Aviation service provider's direct operating cost compared to a fleet of conventionally powered aircraft, opportunities for cost reductions in current commuter airline operations through the adoption of the new aircraft were explored. Figure 14 displays the direct operating cost breakdown for three Part 135 commuter airline routes from Saint Louis to nearby cities. The routes studied have an average range of 102 miles which is comparable to the upper bound anticipated for ODM Aviation operations.

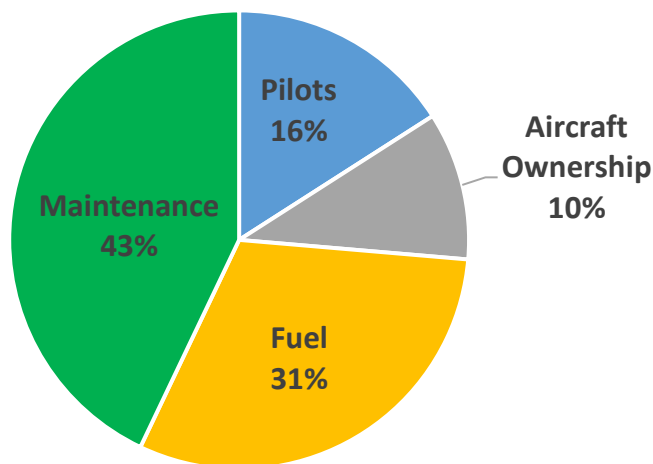


Figure 14. Direct operating cost breakdown for three Cape Air routes from St-Louis in 2015.  
*Data retrieved from the Cape Air 2015 Essential Air Services proposal [83, p. 30].*

A review of Figure 14 indicates that direct operating costs may be most significantly diminished if electric aircraft exhibit lower maintenance requirements, or if electric aircraft energy costs prove to be lower than the comparative fuel costs for conventional propulsion. Together these two categories represent nearly 75% of the direct operating cost for the Cape Air routes from St-Louis. Potential cost differences in terms of pilots and aircraft ownership may be less impactful in terms of the overall direct operating cost due to the relatively low percentage of total costs they represent.

Considering that aircraft maintenance accounts for the largest wedge of direct operation costs for Cape Air, it therefore represents a significant opportunity for cost savings through electric aircraft. A 2016 investigation by Georgia Tech into the operating economics of aircraft for on demand air services concluded that distributed, full-electric propulsion aircraft have the potential to reduce maintenance costs compared to conventionally powered commuter aircraft for mission ranges of less than 200 nmi [67]. The study proposed this could be achieved because electric aviation motors have fewer moving parts than conventional aviation engines and therefore will exhibit reduced maintenance needs and engine overhaul requirements.

Although electric aircraft may have reduced engine maintenance and overhaul costs, the overall aircraft maintenance costs may not actually be reduced due to the cost of battery replacement. Electric aircraft battery cells will require replacement every few hundred to few thousand cycles. While changing batteries may be a relatively simple process requiring fewer labor man-hours than the overhaul of a conventional engine, the expense of new batteries may be a significant proportion of the initial acquisition cost of the vehicle. If electric automobiles are used as a proxy, battery replacement for some automobiles initially cost as much as 50% of the acquisition cost of the car. However, improving battery production and recycling technologies have dramatically reduced

these costs over the past decade and may continue to lower battery replacement costs if the market does not exceed production capacity [84].

Aircraft fuel (energy) represents the second largest direct operating cost for the three routes presented in Figure 14. The energy usage study of an SR-22 equivalent aircraft in Section 2.3.1.2 found that electric propulsion may reduce in-flight energy usage by as much as 76% compared to conventional propulsion. Assuming the national average electricity price and 100LL aviation fuel prices are ¢10.41 per kWh and \$4.71 per gallon, respectively, then Figure 15 displays the potential energy cost savings of electric aircraft operation compared to conventional aircraft operation.

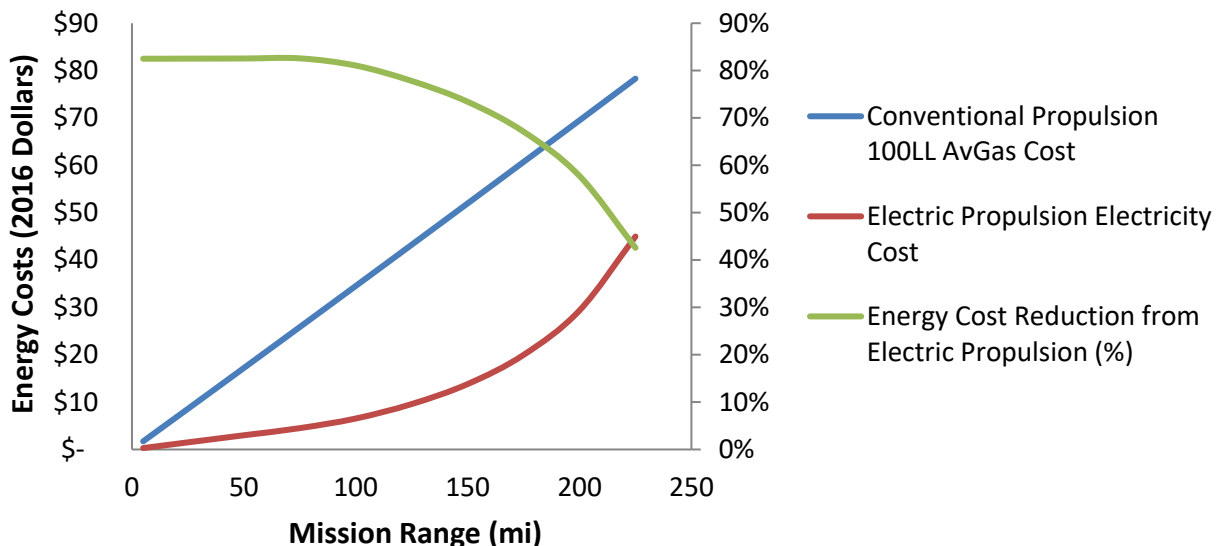


Figure 15. Comparison of energy costs between full-electric and piston engine aircraft

Figure 15 indicates that for missions of up to 100 miles in range, energy costs could be reduced by as much as 83% through the use of full-electric aircraft. Furthermore, if off-peak battery charging were employed, or industrial electricity pricing schemes were negotiated, the energy cost savings could be even larger for full-electric aircraft.

If an average energy cost reduction of 75% is assumed for short-range ODM Aviation missions that use full-electric aircraft, a 23% reduction in the overall direct operating costs for the airline would be realized. Furthermore, because helicopters are typically used for the VTOL missions proposed for ODM Aviation rather than the fixed-wing aircraft considered in this first order analysis, the potential cost savings from the adoption of electric aircraft may be more pronounced.

The final two wedges of direct operating costs represent pilot wages and the costs of aircraft ownership. These two wedges combine to represent only a little more than a quarter of the direct operating cost for these Cape Air routes. Therefore, cost variation between conventionally powered aircraft and electrically powered aircraft in terms of pilot wages and ownership costs will have a lesser impact on the overall direct operating costs. Near-term ODM aircraft are likely to have similar pilot qualification requirements and costs to current vehicles, however the far-term implementation of advanced automation in ODM aircraft may reduce piloting costs. ODM operators purchasing a fleet of new electric aircraft may also have significantly higher near-term ownership costs than reported by Cape Air (which uses legacy aircraft). This would be especially

pronounced if the acquisition cost of electric aircraft is greater than the cost of an equivalent conventionally powered aircraft.

The differences between the vehicles operated by Cape Air and the vehicles (electric or conventionally powered) that are likely to be used by ODM operators represents a limitation of the direct operating cost analysis presented in this sub-section. Direct operating costs are sensitive to the type of aircraft operated by the airline, and the total costs or relative percentages of each expense wedge may vary dramatically for different aircraft. Cape Air utilizes twin engine, piston powered Cessna 402 aircraft [83]. The 402 can carry up to nine passengers and a pilot and is therefore about twice as large as the SR22 which was used as the baseline aircraft for the electric propulsion energy consumption study. The reduced pilot to passenger ratio of the full-electric SR22 equivalent considered in this analysis would therefore have a larger percentage of direct operating cost accountable to the pilot wages than found for Cape Air.

Secondly, the Cessna 402 aircraft are legacy vehicles that were last manufactured in 1985. Due to the average age of the Cape Air fleet, it is likely the percentage of direct operating cost due to maintenance is larger than it would be for an ODM operator with newer vehicles. Furthermore, because the Cape Air fleet is composed of older planes, it is also likely the percentage of direct operating costs due to aircraft ownership is less than for ODM operators as the Cape Air fleet is already fully depreciated and required less upfront financing to acquire.

### **2.3.2 Telecommunications for ODM Aviation Overview**

A second technology that is proposed to enable ODM Aviation networks is advanced telecommunications through pervasive smart phone availability. Transportation networks have traditionally had no mechanism to gather real-time, fine grained demand information. As a result, either fixed service schedules were set that the consumer had to conform to, prior booking was required to schedule a particular service, or a service provider (such as a taxi network) attempted to balance supply and demand within a small geographic area based upon prior experience.

Today, however, ground-based ODM service providers such as Uber and Lyft have displayed the capacity for smartphones to provide the essential data necessary to support the operation of an efficient ODM network. “Telematics,” as the suit of related technologies has become known, is an emerging interdisciplinary field that uses cellular networks, global positional systems, satellite uplinks and vehicle to vehicle or vehicle to infrastructure links to communicate location, navigation, route guidance, congestion management and weather, among other information [64].

Telematics enables ODM networks to efficiently manage assets to meet dynamic demand patterns. Previous iterations of air taxi services were relegated to scheduling customer requests in an attempt to efficiently balance available assets in the network. By collecting a priori knowledge of demand for the upcoming day, efficient, static solutions were developed for the “dial-a-flight” and “crew pairing” problems [36], [85]. The lack of real-time information required these network operations problems to be solved a day or multiple hours in advance of the trips. However, telematics now supports the nearly instantaneous communication of asset location and status to an ODM control network. This supports the dynamic handling of customer requests.

Beyond supporting real-time network optimization, telematics may also enable ODM Aviation networks to implement advanced ConOps that increase airspace throughput and density. For

example, in-vehicle wireless communications have been suggested to “far extend [the driver’s] perception range without expensive long-range sensors, by exchanging local perception information with other vehicles or infrastructure” [86, p. 331]. While ADS-B is an existing example of a system that allows vehicles to share information to avoid collisions, telematics may make future aircraft and pilots more aware of weather events, congested airspace and airports, available ground infrastructure and hazards such as rogue UAS. In other words, new telematics capabilities will allow pilots and aircraft to share information that will make the entire ODM Aviation network operate more efficiently.

### 2.3.3 Autonomy in Aviation Overview

The third proposed enabling technology for ODM Aviation networks is advanced autonomy for aircraft piloting. Autonomy is not new to aviation. By 1912, less than a decade after the Wright brothers’ first flight, rudimentary autopilots were already being implemented in aircraft to hold heading and altitude. Since the advent of computers, commercial aircraft have adopted increasingly capable autopilots that can now fly the aircraft in nearly any weather condition during all stages of flight. However, despite the sophistication of modern cockpit automation, human pilots are required to monitor the systems at all times and take over for many critical phases of flight. Aircraft autopilot systems are one of the most intensely regulated and certified components of a new aircraft and account for a significant proportion of the overall development cost.

In stark comparison, autonomous systems for the operation of automobiles only progressed beyond simple velocity hold (cruise control) capabilities within the past decade. Facing far fewer certification and regulatory restrictions, automobile automation has evolved rapidly with fully autonomous highway driving now available in some Tesla models. Furthermore, fully autonomous vehicles for all driving modes are currently being tested on public roadways by numerous companies including General Motors, Volvo, Mercedes-Benz, Audi, Tesla Motors, Google and (reportedly) Apple [87].

The arms race among automobile manufacturers to produce cars with increasingly higher levels of autonomy is predicated by a substantial list of projected benefits. However, as with any new technology, a variety of challenges have also been identified associated with its implementation. Table 8 provides a summary of the most significant benefits and challenges automation may provide for ground transportation as collected from [88]–[91]; many of these correspond to benefits and challenges for implementation of advanced automation in ODM aircraft as well.

Table 8. Potential benefits and challenges of autonomous automobiles.

| Potential Benefit                                   | Potential Challenge                             |
|---|---|
| Reduced driver workload                             | Increased vehicle and infrastructure cost       |
| Reduced or negated driver wage                      | Novel automation-related risks                  |
| Mobility for non-drivers                            | Security and privacy concerns                   |
| Increased safety                                    | Induced demand that increases congestion        |
| Increased traffic efficiency and reduced congestion | Social equity concerns                          |
| More efficient parking                              | Reduced employment                              |
| Reduced environmental impact                        | Diverted funding for public transportation      |
| Promotion of mobility as a service                  | Reactive regulatory, legal and insurance action |



Despite the numerous proposed benefits, rapid progress of development and large funding sources supporting the development of autonomous vehicles (AVs), the literature is highly varied on the actual realization date of widespread commercial AV usage. This indicates significant underlying uncertainty in the technology readiness and adoption. Ref. [88] is most bullish suggesting AVs may be on the mass market by 2022 to 2025 while Ref. [89] proposes that 2030 to 2040 is a more appropriate time frame. Similar to aviation, perhaps the greatest two threats for ground-based AVs are the development of restrictive regulations and liability concerns for potential accidents.

Many proponents of ODM Aviation view the rapid advancements being made towards autonomous driving as an example of what may be achieved in Aviation. While AVs still face significant implementation challenges, ground vehicle automation is also typically considered more difficult than aircraft automation due to greater variability in road conditions, smaller clearances and the more numerous and dynamic obstacles that cars must handle. Considering these factors, advocates propose that the ODM community may rapidly develop advanced autopilots to reduce or completely remove pilot training requirements [53].

Furthermore, the UAS industry is producing increasingly more sophisticated autopilots that make the small, complex vehicles simple enough for a child to fly. Fully-autonomous flight modes are also available in some UAS models that allow the vehicle takeoff, fly a self-selected route inside the designated area and then land again. Perhaps more impressively, some UAS even have the capability to autonomously follow a moving phone (usually on a person) while filming video and avoiding obstacles in their path. ODM Aviation advocates recognize that as UAS scale for larger payloads and package delivery missions, they may act as a pathfinder for ODM Aviation to follow or appropriate autonomous technologies from.

While automation may significantly increase the demand and profitability of ODM aviation by reducing pilot training requirements (facilitating easier private ownership) or removing costly pilots from each vehicle, automation is less critical than either advanced telematics or quiet and efficient electric propulsion technologies in terms of the implementation of initial ODM Aviation networks. Demand currently exists for helicopter charter services, but is relatively small due to costs and inconvenience of pickup and drop-off points. If novel electric aircraft are developed that reduce operational costs and are able to serve more areas due to a lower noise profile, then demand is likely to increase substantially. Long-term implementation of fully autonomous vehicles will unquestionably increase profitability by removing the costs of paying a pilot for each vehicle, as well as opening up an extra seat or equivalent mass in the vehicle for revenue payload.

#### ***2.4 Market Opportunity and Current Status of ODM Aviation***

There is near universal agreement that a significant market exists for new technologies that reduce congestion and provide individuals with greater mobility. While the United States has relied nearly exclusively on the automobile as the primary mode of personal transportation for the past eight decades, the capacity of the automobile to meet the projected (or even current) levels of demand is diminishing. Authors have identified an emerging crisis where America's highway, bridge and road infrastructure is decaying and substantial mobility capacity stands to be lost unless enormous investments to rebuild are made [3]. Researchers also suggest that the benefits of private automobile transportation have reached an asymptotic state and further investment in increased road capacity will not reduce congestion in the long run [92].

Public transportation modes in dense population centers have, in many cases, also gradually declined in the quality of service provided. As a result of inadequate investment in maintenance and rising wages for employees, public transportation systems have degraded and provide more unreliable services while charging higher fares to cover costs. This has resulted in a reduction in ridership which is leading to additional cuts in service and higher fares. This cyclic cycle, characterized as “Baumol’s cost disease,” has diminished the variety of mobility options available to citizens and further increased the share of the population reliant upon personal cars thereby worsening congestion [93].

The emergence of a sharing economy and mobility as a service may provide relief from these transportation challenges. Removing private cars from the roadways and replacing them with shared vehicles in ODM networks may reduce congestion. Furthermore, ODM Aviation networks may provide a fundamentally new mode of transportation and remove vehicles from the roads, particularly for long distance commutes.

Perceiving that ODM Aviation may fulfill this enduring transportation need in metropolitan areas, researchers and manufactures have attempted to clarify the market opportunity and back out vehicle and operations requirements necessary to operate a competitive service. Aircraft-based aviation in metropolitan regions is often described as a “long tail” market. In a long tail transportation market there is a relatively low demand for travel between any two given points, however there are a large number of these origin/destination pairs demanded.

In other words, while traditional air carriers have converged on a hub and spoke model providing services with a few, large aircraft flying routes connecting high demand city pairs, ODM Aviation seeks to fly numerous point-to-point flights where any one route has low demand [53]. The overall number of people transported by the few flights of the major air carriers may be similar in magnitude to the demand people have for point-to-point flights with ODM Aviation companies. Figure 16 presents a visualization of long tail markets and the types of aviation services that may be categorized as servicing these markets.

Research has shown that a consumer’s willingness to select aviation transportation and pay an increased premium over other mobility modes, such as public transportation or personal car transportation, depends upon three primary attributes: travel cost, in-vehicle travel time, and out-of-vehicle travel time (first mile/last mile ground transportation to airport) [58]. Long distance trips have therefore typically produced a high demand for air transportation as significant time savings are realized by the consumer and airlines experience positive operational feedbacks that reduce costs per seat mile. Furthermore, for long distance trips consumers are willing to tolerate significant first mile/last mile transportation distances to airports and the time consuming security and check-in processes.

Although consumers demand more rapid short-distance transportation (especially in congested urban areas), it has historically been difficult for air transportation to serve these markets because the cost per passenger mile increases for short-distance flights and the first mile/last mile ground transportation to and from airports becomes a more significant proportion of the trip block time [52]. Therefore, in order to compete with automobiles for short-distance transportation, ODM Aviation must develop new VTOL ground infrastructure that are located closer to demand centers than current airports; they must also reduce the cost per passenger mile for flights compared to

current helicopter operations. Market demand studies have suggested that to be competitive with ground modes of transportation, ODM aviation will need to provide air service with fares between \$1.25 and \$4.00 per seat mile for inter-urban trips (approximately 200 miles) [10], and on the order of \$0.5 to \$1.0 per seat mile for intra-urban trips [58].

Figure 16 is a diagram frequently used in the ODM community that notionally displays how new aircraft, infrastructure and telecommunication technologies may enable ODM aircraft operators to serve numerous, low volume routes in inter-urban and intra-urban markets. Known as a “long tail” market [94], the inter and intra-urban missions individually have relatively low demand and draw in customers from a relatively small geographic area. However, the large number of these missions create a total market share that is potentially on the scale of existing airline operations [53], [67]. In comparison, the traditional aviation markets towards the left of the curve have very high demand for a small set of routes between common city pairs and draw in demand from a large geographic area.

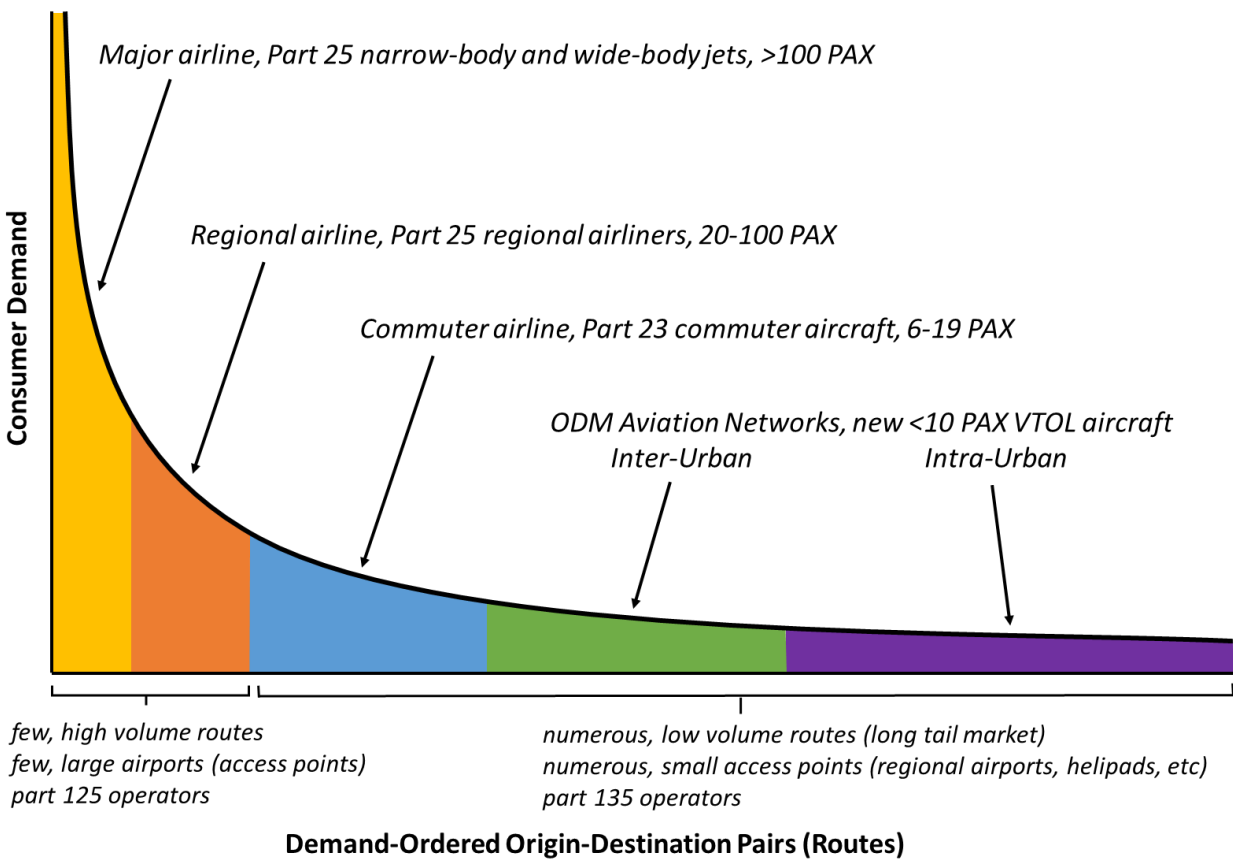


Figure 16. Notional diagram indicating how new aircraft, infrastructure and telecommunication technologies may enable ODM operators to serve the “long tail” of the transportation market. *Image adapted from presentations by Bruce Holmes and research by Harish et al. [67, p. 2].*

While Figure 16 is useful to conceptualize the type of markets ODM Aviation may initially enter, it does not accurately display the actual demand distribution for Aviation services. The reason for this is that the demand indicated on the y-axis is dependent upon the geographic resolution used in the analysis. For example, the demand for a specific major airline route represents only the

origin-destination pair of the two airports on the route. In reality, the passengers using this service must use ground transportation to and from their actual origin and destination points. This has the effect of concentrating customers from a large geographic area into the routes between major cities and inflating the demand estimated for that city-pair route.

The demand for a specific ODM Aviation route, on the other hand, may represent a route from a specific address to another specific address (a very fine geographic resolution). This suggests that as vehicle technologies improve, it may be possible that ODM Aviation services could provide long-distance direct flights to and from flexible locations and reduce demand for the airport-centered airline routes. In such a case, Figure 16 would become flat as concentrated routes would cease to exist.

As presented in Section 2.3, a variety of new technologies are proposed to significantly reduce the operational costs of ODM Aviation aircraft and enable VTOL access to urban areas. Numerous research programs and companies are actively working to bring a viable vehicle to market to access the untapped potential of ODM Aviation in metropolitan areas and personal air transportation. Table 9 displays the list of companies that have publically announced intentions to develop aircraft that may participate in ODM Aviation networks. While no vehicle has yet been brought to market, many of these companies expect to have first deliveries by 2020.

Table 9. Manufacturers proposing to develop and produce ODM aircraft (in alphabetical order).

| <b>Manufacturer</b>            | <b>Vehicle Type</b>                       |
|--------------------------------|---|
| Aero Electric Aircraft Company | Solar-electric trainer aircraft           |
| AeroMobil                      | Roadable, conventionally powered aircraft |
| Airbus A <sup>3</sup>          | Electric VTOL multicopter                 |
| Aurora Flight Sciences         | Electric VTOL aircraft                    |
| Carter Aviation                | Conventionally powered VTOL aircraft      |
| EHang                          | Electric VTOL multicopter                 |
| Elytron                        | Conventionally powered VTOL aircraft      |
| Eviation                       | Hybrid Al-Air+LiPo aircraft               |
| Evolo                          | Electric or hybrid VTOL multicopter       |
| Joby Aviation                  | Electric VTOL aircraft                    |
| Kitty Hawk                     | unknown                                   |
| Lilium Aviation                | Electric VTOL aircraft                    |
| Moller International           | Conventionally powered VTOL aircraft      |
| Mooney International           | Electric trainer aircraft                 |
| Terrafugia                     | Roadable, conventionally powered aircraft |
| XTI Aviation                   | Conventionally powered VTOL aircraft      |
| Zee.Aero                       | Electric VTOL aircraft                    |

The companies listed in Table 9, along with NASA and the FAA, are the primary stakeholders involved in the development of ODM Aviation. This thesis engaged these entities to provide notional ConOps, aircraft capabilities, projected market demands, potential challenge mitigation proposals, and feedback on the results of this research. The collaborative development of key technologies and procedures is recognized as important by this community during the nascent periods of the industry.

Finally, UAS operators and manufactures are also seeking to capture a portion of the demand for metropolitan air transportation. While UAS may not move passengers for many years, they may remove automobile trips from the roads and reduce congestion by completing tasks that previously required travel. For example, Ref. [8] identifies 135 potential UAS applications for UAS, many which may displace ground trips, and Ref. [95] provides an in-depth review for how UAS package delivery may remove a substantial number of consumer and delivery vehicle ground trips.

Outside the aviation community, transportation and urban planning experts warn that when it comes to transportation and congestion, “technological fixes are neither acceptable nor affordable... [and] may solve immediate problems only to cause greater problems later...[by] support[ing] a lifestyle that is damaging to the long-term social good” [96, p. 155]. ODM Aviation has the potential to access a large, untapped market, produce a significant return on investment, potentially reduce the burden of congestion and provide new capabilities to millions of Americans as outlined in Table 3. However, the Aviation community and the nation at large must be mindful to grow this new industry responsibly and address known concerns such as noise, pollution and equity, as well as previously unknown challenges, some of which this thesis identifies.

## ***2.5 Systems Approaches to Initial Requirements Definition***

This section of the literature review does not focus on ODM Aviation, but rather provides a brief overview of various approaches currently used for early-phase conceptual design and requirements definition. As a reminder, while the three research questions of this thesis concern evaluating the operational potential for ODM Aviation networks in metropolitan areas, to address these questions it was necessary to first develop a holistic approach for conceptual design. A brief discussion is provided to explain why existing approaches to initial requirements definition were not sufficient to apply to ODM Aviation networks, identify constraints and externalities, and address the posed research questions.

Traditional aircraft design texts typically assume that a set of specifications (requirements) already exists, often provided by the customer, that were developed in consideration of a broad range of factors. Jan Roskam suggests that these specifications may be derived from “independent market surveys,” “customer requests,” or “operational requirements” [76, p. 3]. John Anderson states that in rare occasions conceptual design may forgo a concrete set of specifications and rather result from “the desire to implement some pioneering innovative new ideas and technology” [71, p. 382].

In the first requirements definition situation, the *completeness* of the requirements is essential to the realization of a useful product. Therefore the process by which such requirements are defined is of particular interest to this research. The second situation, which may be thought of as finding a problem/market to address with an a priori technological solution, may create downstream program challenges as the technology was not initially developed with respect to holistic requirements of the specific application at hand.

The *NASA Systems Engineering Handbook* provides further insight into the factors considered for traditional engineering early-phase conceptual design and the definition of design specifications. The handbook describes the purpose of this period of conceptual design as:

*To produce a broad spectrum of ideas and alternatives for missions from which new programs/projects can be selected...determine feasibility of desired systems, develop*

*mission concepts, draft system-level requirements, [and] identify potential technology needs” [97, p. 7]*

The handbook continues by stating that stakeholders, mission ConOps, technical performance measures, cost, schedule, risk, and technology readiness level (TRL) should all be considered to develop these system-level requirements and create alternative designs [97, p. 22]. While these factors support engineers to assess the technical and managerial feasibility of potential programs, they do not necessarily address factors such as legal and regulatory compliance, environmental impact or social acceptance, among others.

Reaching into the literature of requirements engineering, a few approaches to consider these peripheral disciplines emerge. Requirements Engineering (RE) “is concerned with finding out about the future situation...gathering information and considering possible options, and ... identifying what should be designed in order to meet some perceived future need” [98, p. 2]. This same text on RE introduces nine communities, ranging from marketing to sociology to formal computer science, and documents dozens of different techniques these communities have developed to produce requirements. While each community may be effective at developing requirements that address needs from their specific domain, programs that do not elicit requirements from each domain may lack critical viewpoints and specifications necessary for holistic design. Technically complex, novel products are especially susceptible to lacking RE experts in non-technical fields such as sociology and law.

Furthermore, a domain-centered approach to requirements definition may neglect system properties and needed requirements that emerge from interactions between the disciplines or the interaction of the system with its environment. For this reason, RE has recognized the importance of developing “non-functional” requirements that address emergent system properties and influence factors for complex systems [99], [100].

When implemented, components of a system or interactions between the system and its environment may cause emergent properties and attributes to exist that could not be predicted by analysis in any single discipline. Non-functional requirements therefore seek to identify potential emergent values and set expectations for how they will be expressed by the system. These non-functional requirements ideally would capture the regulatory compliance, environmental impact and social acceptance aspects, among others, of ODM Aviation operations and technologies that represent significant and perhaps traditionally non-technical challenges to implementation.

Considering these factors, techniques for RE including soft systems, participative design and user-centered design “encourage the requirements engineer to consider social, political and organizational issues as part of the requirements investigation” [98, p. viii]. While these methods show promise to facilitate more comprehensive holistic analysis that considers numerous key domains beyond engineering, except for in the computer sciences these methods have not become commonplace RE approaches for traditional systems engineering.

Another area of literature that has promoted similar techniques to define more holistic requirements is enterprise architecting. Similar to soft systems methodology for RE, the ARIES framework proposed by Nightingale & Rhodes employs ten “lenses,” or domain specific viewpoints, to develop requirements for the selection of an appropriate concept architecture for an

enterprise [14]. This concept of viewing a product or system from multiple viewpoints appears to be key to identify potential challenges and constraints.

Moving beyond engineering, the environmental policy community has developed an approach called “backcasting” that is intended to develop policy requirements to “produce the desired technical, organizational, and social transformations” without “allowing the agenda to be captured by the incumbents” [101, p. 1051]. As stated by Ref. [102, p. 172], “instead of starting with the present situation and projecting prevailing trends (forecasting), the backcasting approach designs images of the future that represent desirable solutions to societal problems and casts back to the present.”

Framing backcasting in terms of engineering conceptual design, the methodology may enable innovators to identify how radical new systems or products will interface with society in the future, and then work backwards to vet the variety of technological, regulatory, legal, social and other challenges and constraints that must be overcome to reach that projected future. The primary advantage of the approach is that it provides a holistic view of the requirements necessary to advance from the current state to the projected future. Furthermore, it avoids undue focus or bias on specific issues or potential technologies.

A variety of early-phase conceptual design approaches may be used once a complete set of requirements has been developed. For complex systems, such as a network of ODM aircraft, tradespace exploration techniques created for systems of systems (SoS) or technology portfolios may be appropriate [103], [104]. Previous studies have shown the value of tradespace exploration for the architecting and design of transportation systems [105]. Tradespace techniques allow for the satisficing of potentially numerous values from multiple domains through the manipulation of various system design attributes. Furthermore, time dependency and uncertainty in performance, customer, or market needs may be captured in these techniques through the use of *Epoch-Era Analysis* [106].

For situations where the environment, technology capabilities and markets are expected to change dramatically and unpredictably over time, then in addition to conceptual design that prioritizes system value sustainment and resiliency, iterative systems engineering approaches that periodically update system design or operations based on the changing context may be appropriate. The “wave model” for SoS engineering has been proposed to continually re-evaluate a system’s architecture and operations based upon changes in the external environment and periodically update the system as necessary [107]. Similarly, the planned adaptation approach periodically updates policies and regulations to account for new technologies, research findings or social conditions [108]. A lifecycle design management approach may be appropriate to develop during the conceptual design of a disrupting technology such as ODM Aviation that faces many unknowns.

ODM Aviation presents a challenge for traditional early-phase conceptual design, especially for requirements definition, primarily due to the high number of interactions the network has with its environment such as infrastructure, noise, regulation and law. While a variety of conceptual design approaches have been shown to be appropriate for the design of ODM vehicles and networks once requirements have been defined, traditional engineering requirements definition approaches must

be supplemented with concepts from backcasting, systems architecting, and computer science RE to consider the influence of these non-engineering linkages.

This thesis evaluated the operational potential of novel technologies through a first principles review of ConOps to identify challenges and requirements as part of conceptual design. This is not a novel concept. With respect to metropolitan air transportation, Ref. [20] reviewed ConOps to identify helicopter transportation challenges and requirements in 1970, Ref. [65] conducted a similar study for inter-city air taxi services in 2006, and Ref. [52] reviewed a partial ConOps for ODM aircraft in 2016. The approach developed in this thesis builds upon these previous studies. Furthermore, the ConOps analysis is rooted in concepts from backcasting, systems architecting, and computer science RE to support the definition of better requirements for ODM Aviation networks during early-phase conceptual design.

## ***2.6 Consideration of Externalities during Conceptual Design***

Nearly all systems, products and activities result in some form of externality. In some cases these externalities may be positive and provide communities with unintended benefits; these cases represent a missed opportunity by the externality originator to garner revenue or otherwise leverage the benefit. In other cases externalities may be negative and place unintended costs upon some communities; these cases represent a risk to the originator and may result in litigation, regulation or reduced demand feedbacks.

A review of the potential externalities associated with the operation of ODM Aviation services was conducted in this thesis. The purpose was first to identify positive externalities that the industry may maximize and exploit to support the near-term implementation of services. Second, potential negative externalities were explored to identify how vehicle design, network operations or community buy-in could be pursued as part of conceptual design to mitigate associated downstream challenges of the externality.

An “externality” is defined by the Merriam-Webster dictionary as “a secondary or unintended consequence.” Economists often supplement this definition by noting that externalities exist in marketplaces when a cost or benefit of an activity or product is experienced by an agent that did not choose to incur that cost or benefit [109]. A classic example of a negative externality is pollution which may be emitted by an individual or company into the environment and negatively impacts people seeking to enjoy or exist in the environment.

Externalities constitute a risk to their originator because parties negatively affected by an externality may use legal, regulatory, public opinion or other mechanisms to seek retribution. Responses such as these constitute a feedback loop through which additional operational constraints may be levied on an operation. In the case of aviation, for example, the extensive use of fossil fuels for propulsion has contributed a non-inconsequential percentage of the world’s GHG emissions. As a result, the industry is now facing potential feedback reactions from local, national and international governments in the form of carbon taxes, efficiency requirements and market-based measures, among others.

When the costs associated with an externality are quantified and assessed to the originator, such as through a carbon tax in the case of CO<sub>2</sub> emissions, the externality is said to have become “internalized” by the market. The internalization of externalities is a mitigation approach through



which an originator (creator, emitter, etc.) of an externality may avoid feedback risks in the future. However, the success of this approach relies upon the ability of the originator to forecast all potential externalities and then negotiate a price system to compensate losses or accrue benefits.

In practice, many externalities are not identified during the conceptual design phases of a product or system. Policy Impact Assessments (IAs), Social Impact Assessments (SIAs) and Environmental Impact Assessments (EIAs) are commonly used by industries or required by government agencies before implementation to identify the economic, social, environmental or other impacts of a policy, program or project. However, these assessments are typically considered one of the final certification steps of a project and may not be completed until well after the detailed design phase of a project; this is in part because these methods are quite rigorous and require substantial project information and data to complete.

As a result of the last minute nature of the various impact assessments, externalities are often not explicitly identified until they emerge as a consequence of prototyping, implementing or even operating a system. Feedback reactions to externalities in the form of operational restrictions on the system itself are therefore often not anticipated during conceptual design and are only experienced post-implementation. As a result, system operators may experience difficulty modifying equipment or altering operations in response to externalities due to the lock-in of the design or the high costs associated with changing built infrastructure and tooling.

In response to this limitation of current conceptual design methods, the systems-level analysis approach developed in this thesis and pictured in Figure 2 attempted to identify potential externalities that may result from the implementation of ODM Aviation networks, especially those that concern environmental and equity factors. The purpose of the externality analysis presented in this thesis was to make the community aware of some of the unintended impacts urban air transportation may create and how these may represent opportunities or risks for ODM operations. A variety of positive externalities are presented within the opportunities analysis of Chapter 3, and potentially impactful negative externalities are discussed within the operational challenges analysis of Chapter 5.

The last two sub-sections of this chapter review the literature and provide a summary of how externalities that influence social equity and environmental justice may represent near-term development opportunities for ODM Aviation (where the effects are positive) or constitute implementation and scale-up risks (where the effects are negative).

### **2.6.1 Externalities Related to Social Equity**

*Transportation Equity* has historically been used to describe the concept that all people and communities should have a standard, fair baseline level of access to transportation [110]. Because a majority of American cities and communities have been designed around the car as the primary mobility mode choice, transportation equity has often been framed in terms of access to road and highway infrastructure.

It should be noted that *equity* is distinctly different from *equality*. Equity is the concept that all people have a right to some fair minimum threshold of access to a good or service, that the access to this good or service should not be spread too divergently across the community, and that the government has a role to provide impartial, fair and just policy to manage the good or service

[111]. Equality on the other hand implies that all individuals have identical levels of access to a good or service.

Access to a baseline degree of effective and affordable mobility is considered a fundamental need to exist in modern society. Nearly every form of employment, healthcare, education and child care, among other essential services, requires access to transportation. Furthermore, an individual's access to mobility often influences where they live and perpetuates the spatial segregation of the poor, minorities, the aged and the disabled in peripheral or undesirable communities [112].

Transportation equity became a national issue in the 1990s as social movements elsewhere (particularly in environmental justice) gained traction and the central role that transportation played in perpetuating inequity was recognized. Concerns over transportation equity were a central challenge for the implementation of congestion pricing, and significant research in the past decade sought to address these challenges [113]–[115].

While traditional modes that provide equitable transportation options (such as public transit) have not been sufficiently maintained and enlarged to provide high-quality service and geographic coverage of metropolitan regions, the recent emergence of mobility as a service and the sharing economy show promise to provide high quality mobility to currently underserved individuals. Ride sharing services and transportation network companies (such as Uber or Lyft) now offer many individuals access to an automobile at costs comparable to public transportation. For some, journeys that may have taken an hour or more to complete on public transit are now affordably completed in as little as half an hour through ODM car services [116].

These new ground based transportation modes, as well as ODM Aviation, will not only offer new transportation options to consumers but may also induce a variety of changes to city structure and consumer lifestyles that could represent equity concerns. The development of streetcars and automobiles are historic examples of such impact as expressed by Scott Bottles in *Los Angeles and the Automobile* [117, p. 10].

*The availability of mechanized transportation therefore altered both the social and spatial organization of the city. The suburbs, once the retreat of the unskilled and unemployed, suddenly became the preserve of the relatively affluent.*

Because the potential impacts of ODM Aviation present equity concerns in realms well beyond transportation, the focus of this thesis was broadened to the more comprehensive concept of *social equity*.

## **2.6.2 Externalities Related to Environmental Justice**

Environmental justice is defined by the U.S. Environmental Protection Agency as “the fair treatment and meaningful involvement of all people regardless of race, color, national origin, or income, with respect to the development, implementation, and enforcement of environmental laws, regulations, and policies” [118]. Consistent with the aims of social equity, the primary purpose of environmental justice considerations is to provide all individuals with a fair, baseline level of protection from environmental and health hazards, and an equal opportunity to make personal lifestyle decisions and participate in the policy-making processes to enhance their wellbeing beyond this baseline.

Environmental justice activists seek to identify and address industries, governments and individuals that impose unequal environmental burdens upon a community based upon differences in its attributes (race, ethnicity, wealth, power, etc.), geographic location (inner cities, suburbs, rural areas, etc.) or employment (blue collar, white collar, etc.) [119]. Environmental justice concerns and campaigns have impacted numerous industries since the 1970's including waste disposal, resource extraction, highway planning, and airport construction, among others. Perceived as threats to the core of democracy and equal rights, environmental justice issues have frequently garnered a national spotlight resulting in damage to the legitimacy or public perception of the polluter. Two recent examples of national environmental justice issues were the 2014 Flint water crisis and the 2016 Dakota Access Pipeline protests.

The transportation sector has frequently been a focal point for environmental justice concerns. Transportation infrastructure pervades every community, and nearly all transportation vehicles have potentially harmful health impacts including emissions, noise, physical hazard (safety) and water contaminants. Large transportation infrastructure, such as highways or railways, were often routed through poorer communities and viewed as a textbook example of the unjust distribution of environmental burdens.

This thesis reviews the implementation and operation of ODM Aviation services with respect to numerous environmental justice considerations. Community noise impacts from operations, land use requirements for ground infrastructure, safety considerations from vehicle operations and emissions, as well as air and water impacts were all reviewed. However, greenhouse gas (GHG) emissions from ODM Aviation were investigated in greater detail due to the significant international political and regulatory attention that has been given to this specific externality. It was hypothesized that if ODM Aviation significantly increase GHG emissions compared to current modes of urban air transportation then operational limitations may be imposed by local or state governments. On the other hand, if ODM Aviation services reduce GHG emissions compared to current modes, then operators may be able to leverage this positive externality to foster the near-term implementation of these networks.

On a global scale, the unequal distribution of costs and benefits from climate change (a primary externality of transportation) has prompted significant international activity to address greenhouse gas emissions. Transportation as an economic sector accounted for 14% of the worldwide GHG emissions in 2010, and 23% of the energy-related CO<sub>2</sub> emissions [120]. Furthermore, while many other economic sectors are effectively reducing total emissions through mitigation policies and technologies, CO<sub>2</sub> emissions from transportation grew 44% between 1990 and 2007 and are expected to account for over half of all global CO<sub>2</sub> emissions by 2050 due to the dramatic increase in worldwide demand for mobility [121]. With the development of the Paris Agreement at the United Nations Framework Convention on Climate Change in 2016, GHG emissions from all sectors will be strictly scrutinized by signatory governments moving forward.

Aviation has often been a challenging sector for GHG reduction targets. As one of the most energy intensive forms of transportation, aviation contributed 2.5% of the world's GHG emissions in 2014 [120] and is expected to climb to as much as 18% by 2050 [121]. Moreover, unlike automobile transportation, which has been described as "the most democratic of pollution sources" as it is available to nearly every American [122, p. E1], aviation is transportation primarily for the middle and upper classes. Figure 17 reveals a dramatic increase in aircraft utilization by individuals who

have higher incomes [123]. This characteristic inherently exposes aviation to environmental justice concerns (as well as social equity concerns). Aviation induces demand for long distance travel among wealthy individuals and significantly increases their contribution of GHG emissions and the associated environmental externalities.

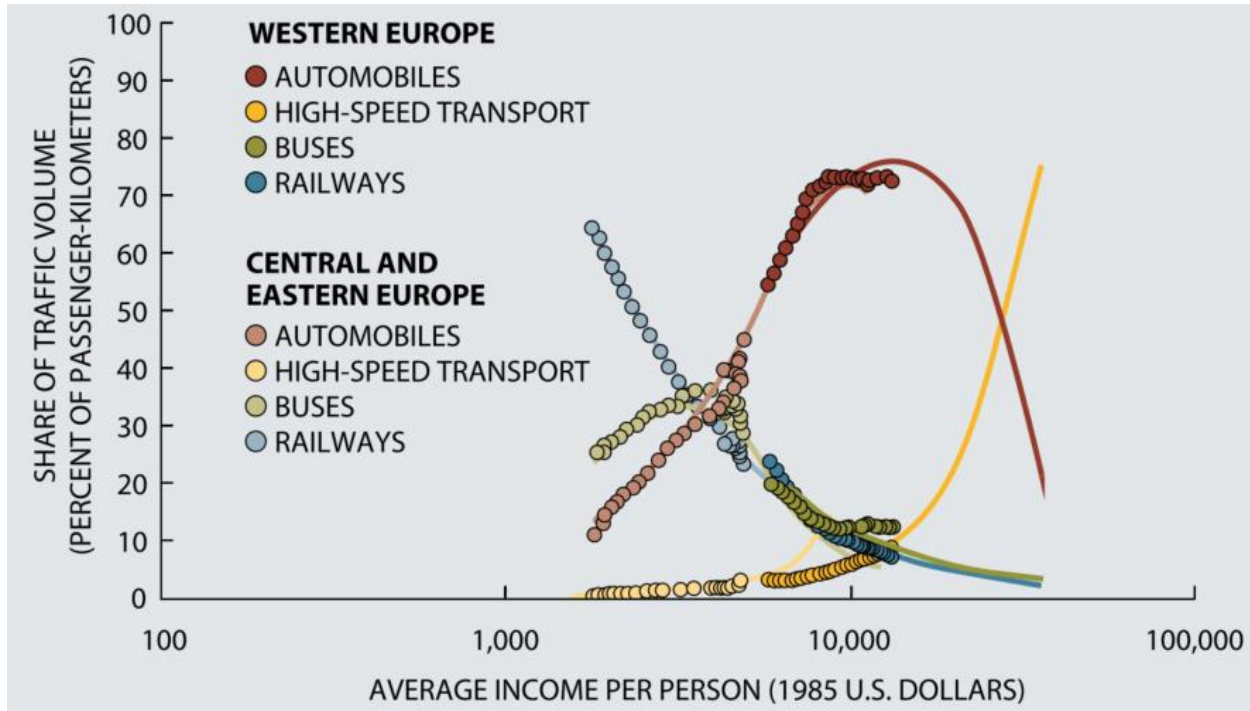


Figure 17. Consumer utilization of aircraft transportation modes increases with income and is primarily available for the middle and upper classes. *Image reprinted from “The Past and Future of Global Mobility” by Schaefer & Victor [123, p. 60].*

ODM Aviation is entering an aviation community and world that is more aware of environmental justice considerations, climate change and GHG emissions than at any previous time in history. The International Civil Aviation Organization (ICAO) recently developed a market-based measure scheme to offset and reduce CO<sub>2</sub> emissions from international flights with the goal of carbon neutral growth from 2020 onwards [124]. While this agreement does not apply to domestic ODM operations, it may indicate that future emissions reduction agreements could impact domestic activities. Numerous states have adopted their own ambitious plans for GHG reductions. Massachusetts, for example, has committed to reaching carbon emissions reductions of 80% below 1990 levels by 2050 [125]; California has committed to the same goal [126]. Furthermore, the Intergovernmental Panel on Climate Change (IPCC) has specifically recommended that the following steps be taken to reduce GHG emissions from passenger transportation [120, p. 603]:

1. Avoid journeys through urban densification and telecommunication technologies.
2. Shift modes to lower-carbon transport systems such as public transit, walking or cycling.
3. Lower the energy intensity of transportation through new vehicles and higher load factors.
4. Reduce the carbon intensity of fuels through electrification or alternative fuels.

ODM Aviation appears to be relatively at odds with the first two, and to some degree the third, of the IPCC recommendations. Finally, the IPCC also specifically cautions transportation planners

against inducing additional travel demand through the expansion of airport infrastructure [120, p. 631].

ODM Aviation may face significant operational constraints as a result of environmental justice externalities, especially in response to noise and GHG emissions. However, there are also numerous positive externalities that may be leveraged by near-term operators to support the implementation of ODM networks in communities and metropolitan areas. In either case it is necessary that the ODM Aviation community considers environmental justice externalities during conceptual design.



### 3 ODM Aviation Market Opportunities and Case Study Definition

While the previous chapter reviewed historic attempts to implement urban air mobility services and the current approaches used for requirements engineering during early-phase conceptual design, this chapter presents an assessment of the market potential of current day ODM Aviation proposals and defines the system boundary for ODM Aviation services in Los Angeles.

First, the business opportunities for air transportation services in metropolitan areas were examined. This review provided an understanding of the types of missions ODM aircraft may fly and the business architecture, or concept, under which they may be operated. The business opportunity analysis was aircraft and geographic location agnostic. However, some basic requirements including V/STOL capability became apparent.

Second, the Los Angeles basin (and the greater southern California region) was selected as an initial case study due to the expectation that it may uniquely support the near-term implementation of ODM Aviation networks due to multiple favorable traits such as generally good weather, a significant number of current helipads, and severe surface transportation congestion. A system boundary was defined to encompass this area based upon consumer demand and anticipated ODM missions characteristics.

Third, a variety of positive externalities that may result from the implementation of ODM aviation services were evaluated. These externalities represent ancillary benefits to an urban area that may potentially be leveraged by ODM Aviation operators as opportunities to gain government funding, public acceptance, or market share. As such, a variety of mission qualities and impacts were identified that may promote the near-term adoption of ODM Aviation services.

Figure 18 displays initial steps of the first principles analysis approach developed in this thesis to assess the operational potential of ODM Aviation. The efforts presented in this chapter correspond to the first two steps of the analysis approach, outlined in red. As may be seen, the market analysis and ODM Aviation adoption opportunities identified within this chapter will be used within the next steps of the approach to develop reference missions within the L.A. system boundary.

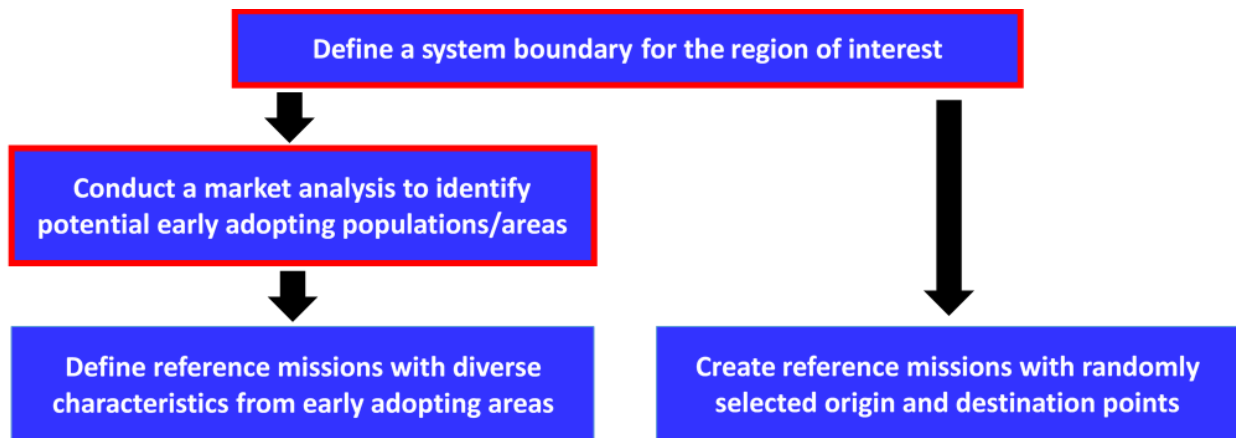


Figure 18. Steps one and two of the approach taken in this thesis to evaluate the operational potential of ODM Aviation define the system boundary and identify characteristics of early adopting markets.

### ***3.1 Promising Mission and Business Concepts for ODM Aviation***

To determine the operational potential of ODM Aviation networks in metropolitan areas, a review of the projected business opportunities and types of missions these networks may engage in was conducted. Four categories of missions were hypothesized that were anticipated to be viable for ODM aircraft with a maximum range of up to roughly a hundred miles.

1. Daily Commute (DC): Aircraft are utilized during business days to transport individuals between a location near their place of residence to a location near their place of work, and vice-versa. These missions are typically short duration and short distance occurring within a city's immediate vicinity. Demand for this mission is bimodal in a 24 hour period representing morning and evening commuting patterns.
2. Weekly Commute (WC): Aircraft are utilized to transport individuals to and from their place of residence and place of work on a weekly basis. These missions are typically long duration and long distance for individuals who chose to live well apart from their place of work.
3. Non-Commute Point to Point (P2P): Aircraft are utilized to transport an individual on a non-commuter trip between two locations. These missions may either be short distance, such as within a city, or longer distance, such as between two cities. This mission may also involve moving goods rather than individuals (courier service).
4. Non-Transportation Mission (NT): Aircraft are operated to provide a non-transportation service. This may include sightseeing, law enforcement, or news gathering, for example.

In Section 2.2.2 a variety of emerging On Demand Mobility business concepts for surface transportation were reviewed. Table 2 related these surface transport business concepts to aviation and found that the sharing network, peer-to-peer rental network and transportation service provider business models may potentially be adaptable for ODM Aviation. Table 10 revisits these three ODM business models, presents specific concepts to implement the given business model in aviation, and indicates which category of mission operations are likely to be conducted for that business concept.

In addition to the five ODM business concepts presented in Table 10, the aircraft in ODM Aviation networks could also be utilized by other non-commercial transportation operators and sectors. While this thesis was concerned only with evaluating the operational potential for commercial ODM Aviation services, Table 11 displays additional markets in which ODM aircraft may be deployed.



Table 10. Business concepts for ODM Aviation.

| ODM Business Model               | Business Concept for Aviation  | Operation Type |    |     |    |
|----------------------------------|--|----------------|----|-----|----|
|                                  |  | DC             | WC | P2P | NT |
| Aircraft Sharing Networks        | <u>Jointly Owned Aircraft</u> : A group of individuals jointly own and operate a single vehicle (perhaps through private fractional ownership). The vehicle is flown as a private operation under FAR Part 91 by the owners.   | ✓              | ✓  | ✓   | ✓  |
|                                  | <u>Rental or Leased Aircraft</u> : An individual may rent or lease an aircraft to be operated as a private vehicle. The vehicle may potentially be rented for short or long durations, one way or round trip, similar to current rental car options.                                 |                | ✓  | ✓   | ✓  |
|                                  | <u>Commercial Fractional Ownership &amp; Cards</u> : Individuals purchase a share of an aircraft and pay additional prices for usage of the vehicle and its professional piloting crew (or autonomous pilot). A company maintains and dispatches a fleet of aircraft to meet demand. | ✓              | ✓  | ✓   | ✓  |
| Peer-to-Peer Rental Networks     | <u>P2P Rental Network</u> : A coordinating company connects pilots looking to rent aircraft with local private owners of aircraft they are certified to fly. The company manages bookings and flight insurance.  |                | ✓  | ✓   | ✓  |
| Transportation Service Providers | <u>ODM Air Taxi Network</u> : A TSP owns and operates a fleet of aircraft through FAR Part 135 certified pilots or full automation.  | ✓              | ✓  | ✓   | ✓  |

Table 11. Alternative, non-commercial ODM business concepts for novel aircraft.

| ODM Business Model         | Business Concept for Aviation   | Operation Type |    |     |    |
|----------------------------|---|----------------|----|-----|----|
|                            |   | DC             | WC | P2P | NT |
| Public Services            | <u>Emergency Medical Services (EMS)</u> : An aircraft is used to transport individuals to a hospital, transfer patients between facilities, or convey medical goods such as live organs or medicines. |                |    | ✓   | ✓  |
|                            | <u>Law Enforcement</u> : An aircraft is used to move personnel and supplies from point-to-point, or to surveil a situation or suspect.  |                |    | ✓   | ✓  |
|                            | <u>Electronic News Gathering (ENG)</u> : An aircraft is used to move personnel and supplies from point-to-point, or to surveil a situation or suspect.  |                |    | ✓   | ✓  |
| Private Air Transportation | <u>Privately Owned Aircraft</u> : An aircraft is privately owned in whole by an individual, business, or family and operated under FAR Part 91 standards.   | ✓              | ✓  | ✓   | ✓  |

These markets are important not only for vehicle manufacturers to consider, but also for ODM Aviation operators. The barriers to entry for new general aviation (GA), privately owned aircraft are far fewer than for commercially flown Part 135 operations. As such, flight experience with novel vehicle architectures and automation is likely to be gained in general aviation first. The public service operations also face fewer barriers to entry than ODM passenger services. Furthermore, EMS, law enforcement and new gathering operations also have decades of operating experience with helicopters. These three public service markets may adopt novel ODM aircraft before ODM Aviation networks are viable. Both GA and public service operations may therefore represent early adopting markets from which prospective ODM Aviation service providers may garner experience.

### ***3.2 L.A. Case Study System Boundary Identification***

The Los Angeles basin was selected for the initial ODM Aviation case study due to the expectation that the metropolitan area was uniquely suited as an early adopter market because of its large consumer base, existing helipad infrastructure and mild weather. It was anticipated that L.A. exhibits a strong market pull for ODM Aviation due to its large population, polycentric city structure and severe roadway congestion. A previous study also identified that the L.A. basin had a significant number of existing helipads in the central business districts (CBDs); these helipads were viewed as a potential asset for ODM Aviation networks [13]. Beyond infrastructure, it was suggested that the mild climate, lack of extreme weather and current presence of numerous helicopter charter operators would simplify the implementation of ODM Aviation networks.

In order to define the case study system boundary, four factors were investigated to indicate where (geographically) near-term ODM Aviation services may be provided in the Los Angeles basin. The four factors considered were:

1. Commuter transportation flows into the Los Angeles metropolitan area
2. Anticipated ODM mission characteristics and aircraft range capabilities
3. Current helicopter charter services in the Los Angeles basin
4. Population density of communities in Southern California

First, the current-day journey to work commuter patterns in the L.A. basin were investigated. Figure 19 displays a mapping of commuting flows from the 2006 to 2010 American Community Survey for Southern California. The flows have been color coded to reveal commuter travel patterns into major metropolitan areas, and heavier line thickness corresponds to flows that contain more daily commuters [127]. It was immediately recognized that Los Angeles County draws in workers from a significant portion of Southern California, even from some communities at a substantial distance inland. These long-distance, inter-community commuter flows may represent potential ODM Aviation missions that were captured in the case study.

Furthermore, the high density of commuter flows in the heavily populated areas immediately surrounding the Los Angeles CBD indicate that ODM Aviation operations may experience significant short distance demand within this inner region. Such *intra*-city flights may have substantially different vehicle requirements and flight profiles compared to the longer distance flights to the outlying communities. The existence of these high density, intra-city commuter patterns indicated the case study should consider a second, inner system boundary to capture the differences between these operations and long-distance, inter-community operations.

Finally, although the three CBDs indicated in Figure 19 appear to be at the center of dense commuter inflows (indicated by color coded lines for each CBD), there are also a number of interconnections between the CBDs themselves or other areas in their “commuter basins”. These *inter-city* commuter routes are especially interesting as they may indicate relatively stable consumer demand for travel along specific routes between nearby CBDs. Considering this finding, the case study system boundary was expanded to contain the Santa Barbara and San Diego CBDs.

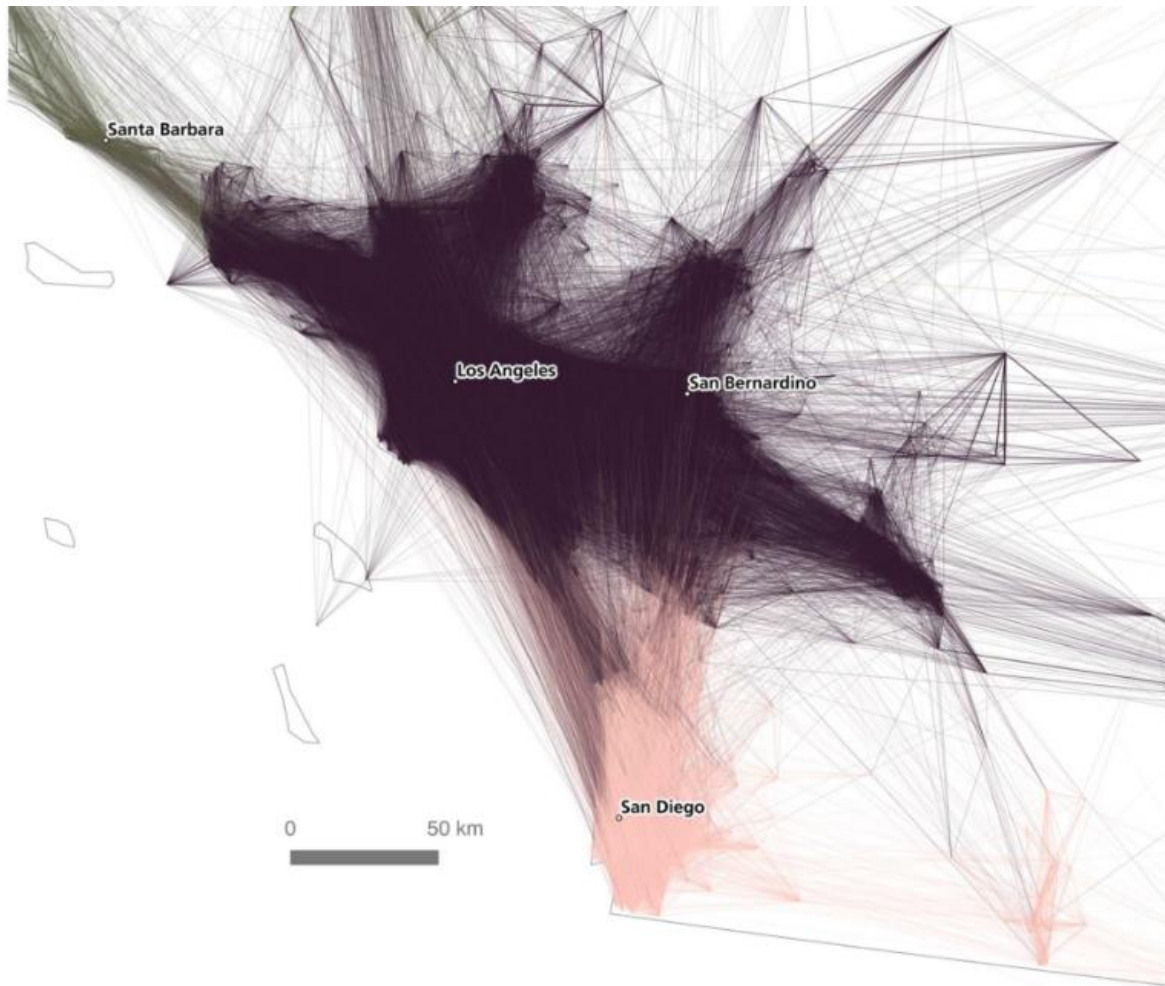


Figure 19. Relative density of commuter flows in the Southern California megaregion revealing a large commuter basin surrounding Los Angeles (purple) with interconnections between the L.A., San Diego (pink) and Fresno (green) commuter regions. *Image reprinted from Nelson & Rae [127].*

While the visual investigation of the commuter flows in Figure 19 revealed some specific cities and regions that were considered in the case study, a useful and more inclusive construct to support the system boundary definition was the concept of a “megaregion” [127], [128]. Megaregions are large networks of metropolitan areas interconnected not only geographically, but also through mutually dependent environmental systems and topography, infrastructure systems, economic linkages, culture, history and land use patterns. The mutual dependency and shared attributes of the cities in a megaregion encourage (or necessitate) transportation between one another and may represent likely initial system boundaries for an ODM Aviation network.

The second resource employed to identify the geographic boundary of the case study was a review of the characteristics of various ODM mission categories and the associated projections of ODM aircraft range capabilities. As presented in Section 2.4, two general types of aviation operations in metropolitan regions have been commonly discussed in the literature. The first type is *inter*-urban flights between nearby cities, conducted either by commuter airlines or ODM Aviation networks. The second type of operation is *intra*-urban flights within a single metropolitan region. These missions are anticipated to be provided by ODM Aviation networks and helicopter charters.

Commuter airlines typically operate fixed-wing, 6-9 passenger, “thin-haul” aircraft between city centers and points of interest, such as from Boston to Providence. As discussed in Section 2.1.4, commuter airline routes are typically less than 100 miles in range. Although current commuter operations are not strictly classified as “on demand” providers since flights are scheduled, specific route may have departures as frequently as every 15 minutes during peak demand periods. While some commuter airline flights may be as short twenty miles in range, these flights are often between two nearby islands or cities, rather than within a single urban area.

In addition to commuter airlines, emerging ODM Aviation operators are also expected to begin inter-urban services between nearby cities or surrounding communities. These operators may elect to use smaller aircraft as they intend to operate non-scheduled flights; on-demand operation makes it difficult to achieve high load factors in large aircraft through customer pooling. If aircraft with V/STOL capabilities are utilized, then off-airport operations into or out of dense CBDs may be possible as opposed to current fixed-wing operations which are restricted to airports.

The second general type of metropolitan aviation operation is *intra*-urban flights within a single urban core and its surrounding satellite cities or residential areas. Intra-urban operations are anticipated to be provided by networks of ODM aircraft that serve a diverse set of routes in a metropolitan area. This contrasts with the relatively set routes of inter-urban operations. Furthermore, because intra-urban operations require aircraft to conduct takeoff and landings in dense urban areas, these types of operations are expected to interact more directly with the non-flying public and experience new challenges traditional commuter airlines have not encountered.

These two anticipated types of metropolitan aviation, distinguished primarily by origin and destination location and mission range, indicated the need to identify a broad system boundary containing other major CBDs and communities in Southern California, while also designating an inner system boundary indicating the immediate metropolitan boundaries of Los Angeles itself.

Current helicopter charter offerings were used as the third resource to develop the case study system boundary. Helicopter charter operations represent the nearest aviation proxy for intra-urban ODM flights. Additionally, some long range helicopter charter flights also represent inter-urban routes that may be served by commuter airlines or future ODM networks. Therefore, the demand and operations of current helicopter charters in L.A. was investigated as a reference point.

Twelve helicopter charter companies located in Southern California were reviewed based on available webpage information. Findings are presented in Table 12, and Figure 20 displays an example range and distribution of missions offered by one of these companies. Clearly, the demand for helicopter charter services extends well beyond the central L.A. CBD into the broader Southern California megaregion.

Table 12. Review of select Southern California helicopter charter companies.

| Helicopter Charter Companies | Home Airport/Helipad   | Services                              |
|------------------------------|------------------------|---------------------------------------|
| Orbic Air                    | Bob Hope (BUR)         | charters, tours, ENG, airport shuttle |
| Helinet                      | Van Nuys (VNY)         | charters, ENG, police, healthcare     |
| Elite Helicopter Tours       | Van Nuys (VNY)         | charters, tours                       |
| Jetboy Helicopters           | Van Nuys (VNY)         | charters, tours                       |
| LA Helicopter Tours          | VNY, BUR, EMT          | charters, tours                       |
| LA Helicopters               | Long Beach (LGB)       | charters, tours                       |
| Star Helicopters             | Hawthorne (HHR)        | charters, tours, air taxi             |
| JJ Helicopters Inc.          | Torrance Field (TOR)   | tours                                 |
| Celebrity Helicopters        | Compton/Woodley (CPM)  | charters, tours                       |
| Island Express Helicopter    | Long Beach Helipad     | charters, tours, scheduled flights    |
| Bakersfield Helic. Charters  | Meadows Field (BFL)    | charters, tours, surveying            |
| Corporate Helicopters        | Montgomery Field (MYF) | charters, tours                       |

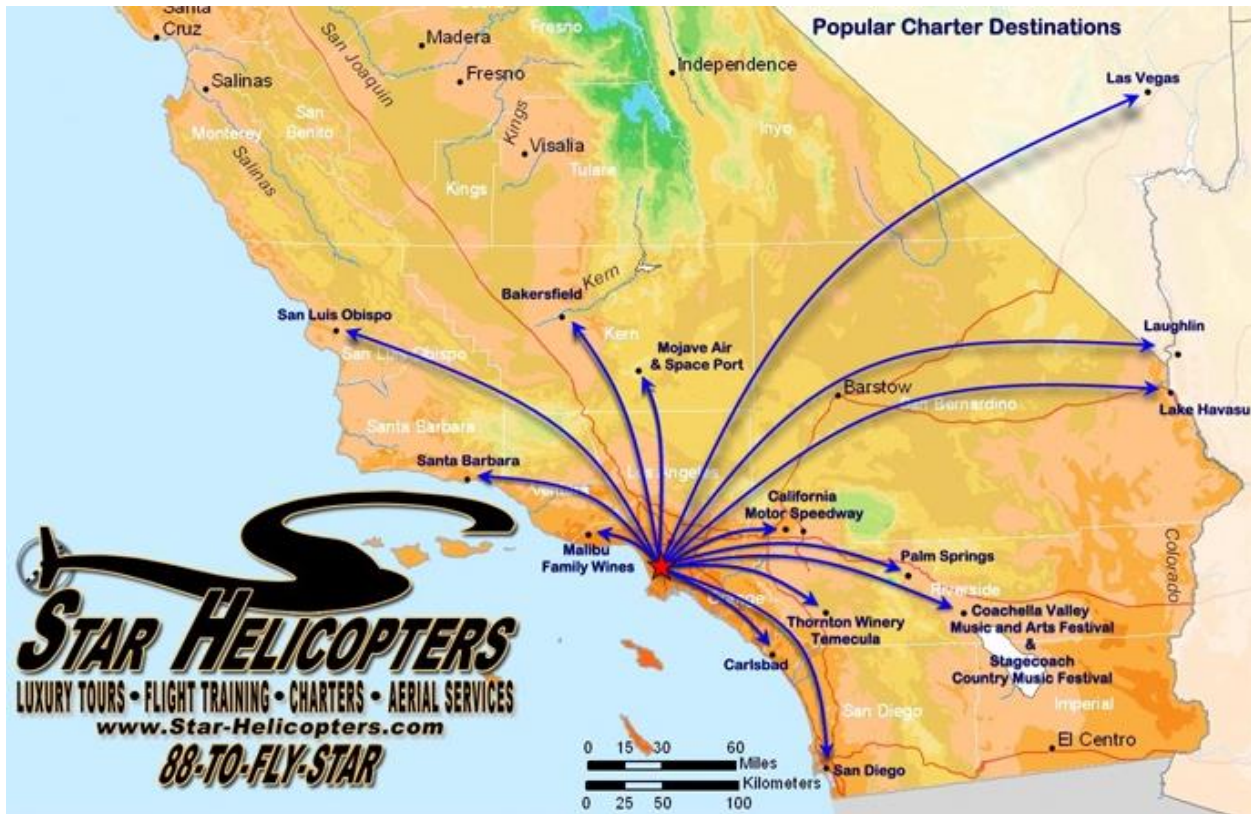


Figure 20. Typical helicopter charter service offerings by a representative L.A. basin company. Image retrieved 6/12/2016 from [www.star-helicopters.com](http://www.star-helicopters.com).

The final factor used to set the system boundary for the L.A. case study was population density. The population densities for the intra-urban areas immediately surrounding the L.A. CBD were thousands to tens of thousands of individuals per square mile. However, many of the communities and areas in the outlying regions of the L.A. basin had a much lower population density, or even zero development. Considering that long distance inter-urban ODM missions are more likely to fly between significant population centers, it was determined that the system boundary should exclude large areas that did not have at least 100 people per square mile.

Considering the insights from the investigation of these four factors, geographic (system) boundaries for both the inter-urban and intra-urban operations were developed for the case study. Figure 21 presents these boundaries overtop a population density map of Southern California.

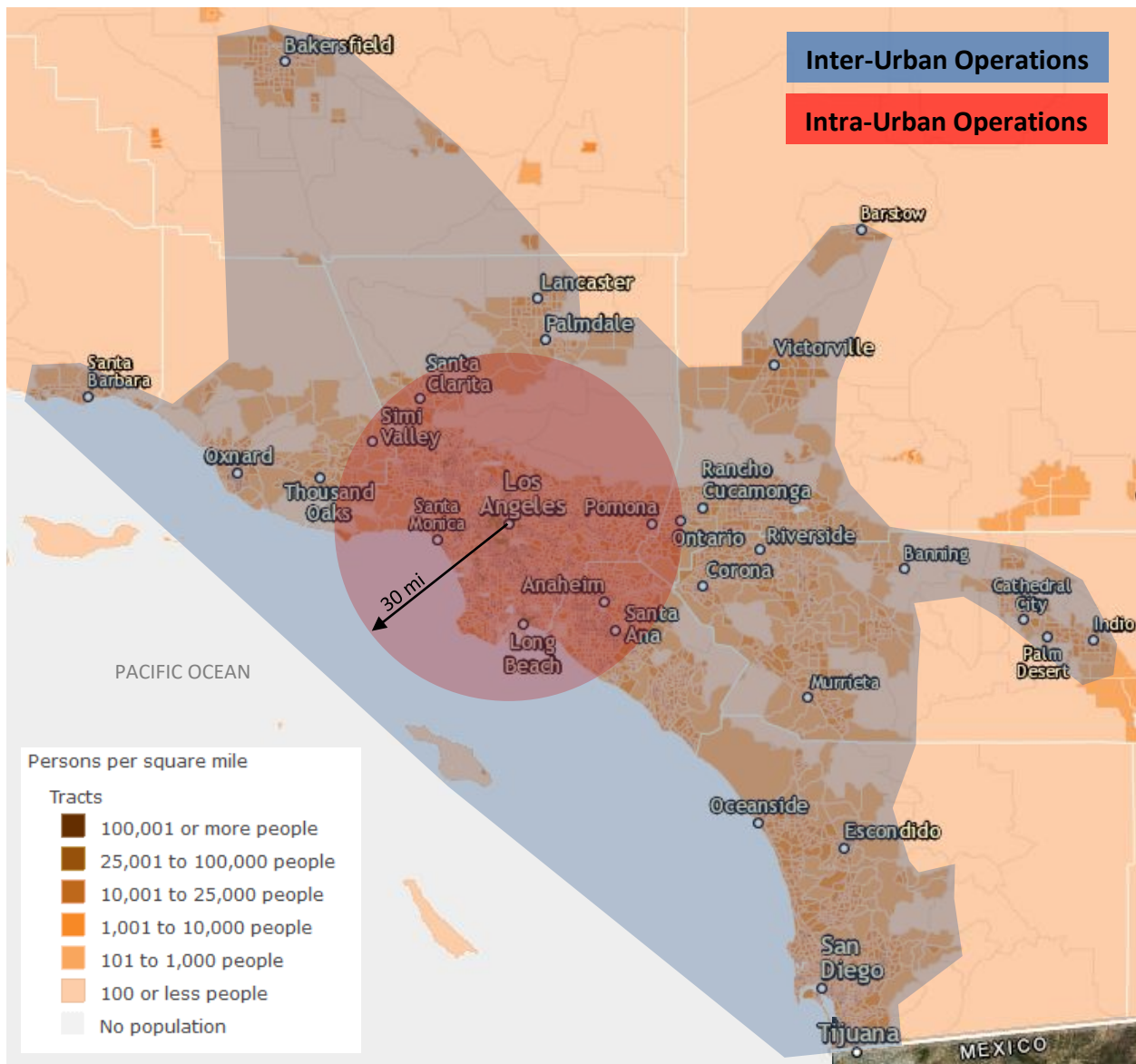


Figure 21. L.A. basin system boundary delineating intra-urban and inter-urban ODM Aviation operations regions. *USA\_Population\_Density map* © 2013 Esri, retrieved from [www.arcgis.com](http://www.arcgis.com).

The outer, irregularly shaped blue boundary contains a majority of the city centers and densely populated regions of the Southern California megaregion. This boundary also encompasses major existing helicopter charter markets within roughly a 125 mile radius of the L.A. CBD. It was assumed that operations within this boundary were reasonable long-range missions for an inter-urban ODM aircraft.

The inner, red circle represents the L.A. basin metropolitan area and its surrounding residential areas and satellite cities; the circle sweeps out a radius of 30 statute miles. Inter-city ODM Aviation services may potentially be provided to residents within this area.

### ***3.3 L.A. ODM Aviation Consumer Demand Estimation and Geographic Locating***

In order to define reference missions and their associated ConOps within the L.A. region, a general understanding of the potential consumer demand for ODM Aviation was developed. Section 3.1 identified four categories of missions that may potentially be viable for ODM aircraft operations. For this case study, the “weekly commute” and “non-transportation” missions were anticipated to represent small market opportunities and therefore were not evaluated. More specifically, it was perceived the weekly commute missions represented a relatively small market sector with limited demand and customers. The non-transportation sector, on the other hand, represented a thriving market that was served by helicopters, and increasingly more so, unmanned aircraft systems. Due to the entrenched position of these competitors, the non-transportation mission category was not considered in this case study as a likely early adopting sector for ODM services.

Having removed these two mission categories from initial consideration, the L.A. basin case study sought to characterize the relative demand for the remaining two categories of missions: daily commute and non-commute point-to-point. The demand for these missions has historically been satisfied through a variety of services in the L.A. basin. Transportation modes such as public buses, commercial taxis, commercial rental car or car share entities, charter helicopters, and private cars provide consumers with a variety of mobility choices. These options exhibit varying attributes a consumer may consider when selecting how to travel such as cost, speed, geographic coverage and reliability. Table 13 displays a notional comparison of a few attributes important to most individuals for a set of common mobility modes they may consider. The performance attributes presented in Table 13 were defined in this research as:

- **Operations Cost**: the direct financial expense to the consumer of utilizing the mobility mode. This may include the cost of gasoline, fares, tolls, and parking, among others.
- **Ownership Cost**: the direct financial expense to the consumer of owning the mobility mode. This may include the costs of maintenance, insurance, certification, and depreciation, among others. Note that consumers bear no ownership costs for commercial or public transportation services.
- **Acquisition Cost**: the direct, one-time financial expense to the consumer of purchasing the mobility mode vehicle. Again, consumers bear no acquisition costs for commercial or public transportation services.
- **Speed**: the relative rate (compared to the other mobility options) with which a consumer may reach a desired destination through this mobility mode. Actual travel speed may vary with weather conditions, congestion and destination proximity to a transportation node (such as a stop or station), so a rough estimate of the average is used.

- Availability: the ability of a consumer to utilize the mobility mode at any given time of day, with or without prior planning.
- Geographic Coverage: the ability of a consumer to reach any desired destination through the mobility mode. Geographic coverage captures factors such as the number and location of potential destination nodes the mobility mode could reach.

Table 13. Comparison of key performance and cost attributes of consumers for common mobility modes.

| <b>Mobility Mode</b>             | <b>Operations Cost</b> | <b>Ownership Cost</b> | <b>Acquisition Cost</b> | <b>Speed</b> | <b>Availability</b> | <b>Geographic Coverage</b> |
|----------------------------------|------------------------|-----------------------|-------------------------|--------------|---------------------|----------------------------|
| <b>Private Car</b>               | Low                    | Medium                | High                    | Medium       | High                | High                       |
| <b>Carpool</b>                   | Low                    | Low                   | Medium                  | Medium       | Medium              | Medium                     |
| <b>Bicycle</b>                   | None                   | Low                   | Low                     | Low          | High                | High                       |
| <b>Taxi/Uber</b>                 | Medium                 | None                  | None                    | Medium       | High                | High                       |
| <b>Bus/Metro</b>                 | Low                    | None                  | None                    | Medium       | Low                 | Medium                     |
| <b>Helicopter</b>                | High                   | None                  | None                    | High         | Low                 | Low                        |
| <b>Hypothetical ODM Aircraft</b> | Medium                 | None                  | None                    | High         | Medium              | Medium                     |

A consumer’s selection of a particular mobility mode (from the set available to them) depends upon their unique set of preferences. Oftentimes these preferences are dynamic and vary with the context, or setting, in which the individual is making their decision. By identifying contexts or specific consumer groups where consumers were more likely to value higher speed transportation, despite the higher relative operations cost, this research identified specific early adopter markets and missions for ODM Aviation. Furthermore, this analysis approach enabled this research to specify geographic regions ODM Aviation may initially serve in the L.A. basin.

For example, individuals traveling long distances or through heavy congestion are likely to express a higher willingness to pay for the increased speed of ODM Aviation. Similarly, it is also probable that individuals traveling to events or popular areas (such as a baseball game or shopping center) expect to encounter significant congestion and may be more likely to desire the capabilities of ODM aircraft. Consumers with high personal wealth may also be assumed to have a higher willingness to pay for ODM Aviation. Finally, it was anticipated that consumers with tight timelines or significant consequences for travel delays, such as individuals traveling to airports or hospitals, may express a higher preference for ODM Aviation.

This research sought to corroborate and confirm the potential demand patterns developed from intuition above by examining three main sources of data:

1. Current helicopter charter services were reviewed to identify market demand in the form of existing metropolitan air transportation missions. Furthermore, the current price supported in the market for these services was evaluated.
2. Census data was examined to identify commuters that experience exceptionally long distance or long duration daily commutes. It was anticipated these individuals may place a higher value on the speed of the transportation mode.



3. Consumer wealth data, gathered through the proxy of home valuation and average household income, was examined to identify wealthy communities that may have a greater willingness to pay for the enhanced value provided by the service.

Figure 22 is a notional diagram displaying the current utilization of various common mobility modes in the Southern California metropolitan region and their associated relative costs. Private car, carpooling, transit and non-motorized (walking or biking) modes were considered based upon commuting data from that Southern California Association of Governments [129]. The associated cost data for each mode was notional and intended to capture the comparative cost of transportation by each mode for the consumer.

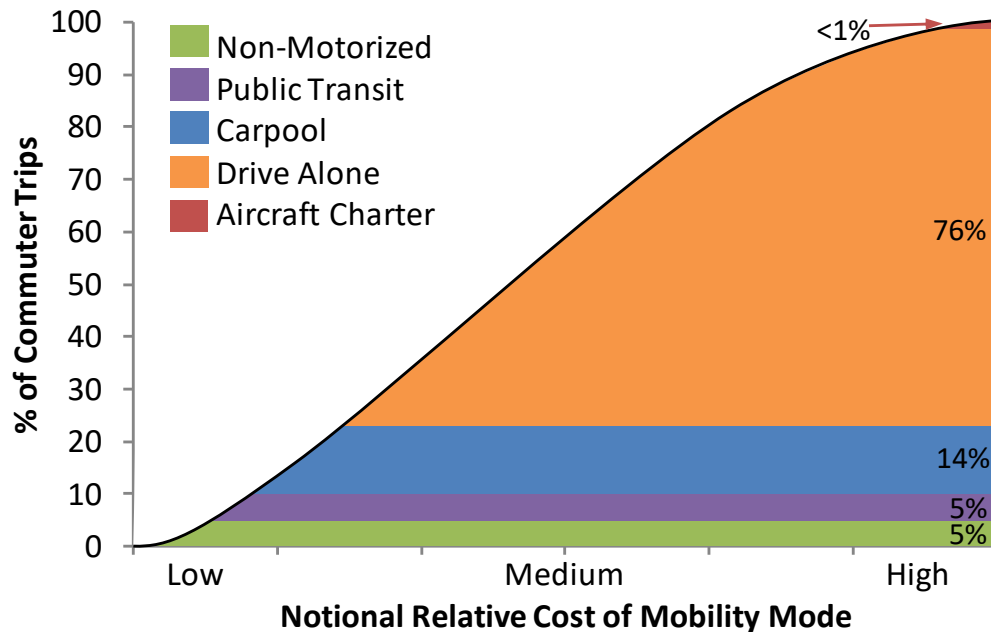


Figure 22. Southern California metropolitan region commuter mobility mode cumulative density function with notional mode costs for the consumer.

Aircraft charter and air taxi services do not currently account for a significant percentage of the L.A. basin mobility portfolio. The distribution in Figure 22 is dominated by individuals driving in private cars; this mode represents over three fourths of all commuter trips. There are numerous studies dedicated to explaining why the L.A. basin came to rely predominantly on private vehicle transportation, and the city’s experience may be taken as a microcosm of the overall American “car culture” [117], [130]. However, for this study the complex factors behind the rise of the car culture are reduced to the simple characterization that private automobiles provided owners with high availability transportation to flexible destinations at reasonable costs and speeds.

Helicopter and aircraft charter services do not represent a significant percentage of the current L.A. basin mobility portfolio in part because they are too expensive for a majority of the market. Furthermore, outside a few specific routes, helicopters do not provide sufficiently increased availability and geographic coverage to justify their cost premium for those who can afford the service.

As presented in Section 2.3 and displayed in Table 13, proposed ODM Aviation networks are anticipated to provide greater availability and geographic coverage than traditional aircraft or helicopter charters, and at lower cost. These characteristics would strategically position ODM Aviation to capture the low cost end of the current aircraft charter market, as well as the high cost, long distance or long duration trips of the personal vehicle market as shown in Figure 23. It is also possible, but not indicated in the figure, that ODM Aviation could capture some passengers from the carpool and public transit modes as well.

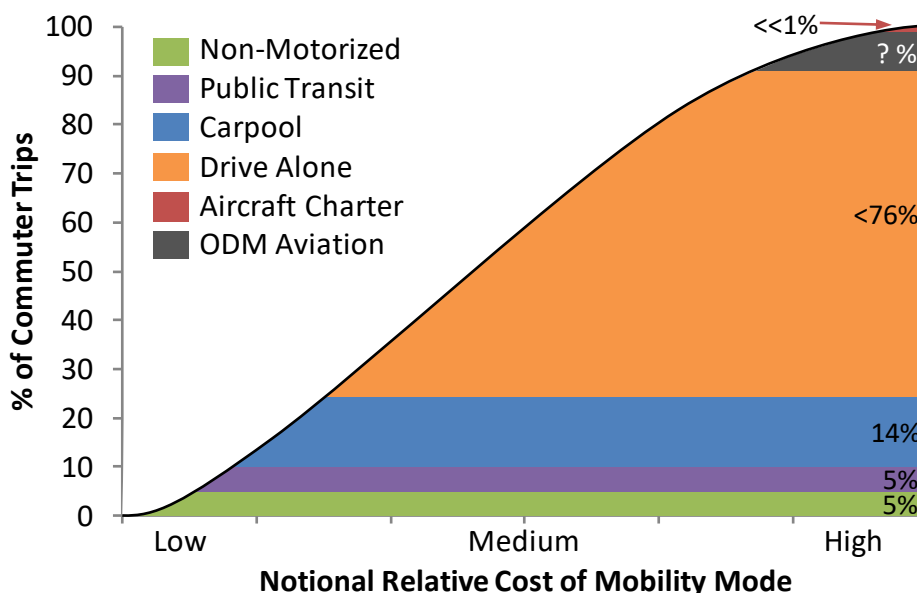


Figure 23. Southern California metropolitan region commuter mobility mode cumulative density function displaying the potential for ODM Aviation to replace low cost aircraft and helicopter charter operations while capturing high cost, long distance automobile trips.

The remainder of this subsection introduces the three data sources utilized to characterize the early adopter markets and define reference missions for the case study.

### 3.3.1 Consumer Demand for Helicopter Charter Flights

As shown in Figure 23, ODM aircraft services are anticipated to attract customers currently purchasing services from aircraft or helicopter charter services. While some companies such as SurfAir, Imaginair, and OXJET currently operate aircraft charters in the L.A. basin, a majority of their offerings extend to locations beyond the inter-urban system boundary and well beyond the intra-urban boundary defined in Figure 21; these long-range charter flights were therefore not considered in this analysis. However, numerous helicopter companies provide charter services within the L.A. basin that are similar to projected ODM Aviation missions, as shown in Table 12.

In order to capture the market’s willingness to pay for metropolitan air transportation, commercial helicopter charter price quotes were gathered for numerous providers in the L.A. region. Table 14 presents information for a variety of popular point-to-point missions for three helicopter charter companies based in Los Angeles. The costs for their services were estimated from publically available price quotes provided on the companies’ websites as of June 2016. While many of these

quotes required the rental of the entire helicopter, a cost per passenger was estimated by assuming the vehicle was flown at full load capacity.

The cost per passenger data represents a lower bound for the price competitiveness of current helicopter operations. The ground distance of the missions was found through the Google Maps™ mapping service as the fastest (though not necessarily shortest distance) route, and the air distance was assumed as the line of sight distance between the origin and destination. Estimating flight range as line of sight distance was a limitation of this analysis and likely underestimated the actual required flight range due to deviations required for air traffic control, restricted airspaces, or weather, for example. The three charter companies reviewed in Table 14 use a variety of helicopters ranging in capability from the piston engine, three passenger R-22 to the turbine engine, five passenger Eurocopter AS 350.

Table 14. Pricing information for select helicopter charter services in the L.A. region.

| Provider           | Route                                      | Distance (mi) |     |
|--------------------|--|---------------|-----|
|                    |  | Ground        | Air |
| Orbic Air          | Burbank to Coachella Music Festival        | 144           | 127 |
| Orbic Air          | Burbank to Dodger Stadium                  | 14            | 10  |
| Orbic Air          | Burbank to Angel Stadium/Honda Center      | 43            | 38  |
| Orbic Air          | Burbank to Santa Barbara                   | 89            | 78  |
| Orbic Air          | Burbank to San Diego                       | 135           | 123 |
| Orbic Air          | Burbank to Palm Springs                    | 123           | 110 |
| Orbic Air          | Burbank to downtown L.A. and return        | 17            | 11  |
| Orbic Air          | Burbank to LAX                             | 33            | 18  |
| Orbic Air          | Burbank to Big Bear                        | 103           | 83  |
| Orbic Air          | Burbank to Orange County (SNA)             | 53            | 45  |
| Jetboy Helicopters | Van Nuys to San Diego                      | 144           | 128 |
| Jetboy Helicopters | Van Nuys to Santa Barbara                  | 79            | 71  |
| Jetboy Helicopters | Van Nuys to Palm Springs                   | 129           | 115 |
| Jetboy Helicopters | Van Nuys to LAX                            | 21            | 19  |
| Jetboy Helicopters | Van Nuys to Orange County (SNA)            | 60            | 51  |
| Star Helicopters   | General Rate - \$1100 per hour for 4 PAX   |               |     |
| Star Helicopters   | HHR to Bakersfield and return              | 119           | 107 |
| Star Helicopters   | HHR to Big Bear and return                 | 109           | 86  |
| Star Helicopters   | HHR to Burbank and return                  | 29            | 19  |
| Star Helicopters   | HHR to Orange County (SNA) and return      | 39            | 32  |
| Star Helicopters   | HHR to Oxnard and return                   | 66            | 52  |
| Star Helicopters   | HHR to Palm Springs and return             | 117           | 103 |
| Star Helicopters   | HHR to San Diego and return                | 123           | 107 |
| Star Helicopters   | HHR to Santa Barbara and return            | 99            | 85  |
| Star Helicopters   | HHR to Santa Monica and return             | 15            | 11  |
| Star Helicopters   | HHR to Auto Club Speedway and return       | 61            | 49  |
| Star Helicopters   | Ontario Airport to Auto Club Speedway      | 11            | 6   |
| Star Helicopters   | HHR to Coachella Music Festival and return | 141           | 122 |

A few key trends were discerned from the data in Table 14 and are discussed below:

1. Non-Substitute Services: The three helicopter charter service providers in Table 14 frequently charged dramatically different fares for services to the same destinations; this characteristic is clarified through Table 15. A price differential for similar transportation services indicates that the helicopter services provided by these three companies were not perceived by the consumers as substitute goods. In other words, customers were willing to pay higher fares in general to charter Star Helicopters than Jetboy Helicopters.

The reason these services were not considered substitute goods may perhaps include the different geographic locations of the companies, the different passenger capacity and capabilities of the vehicles they use, or perhaps the quality of service provided. Only three of the 12 helicopter charter service providers in L.A. were included in this fare analysis, so it is possible that the market is more competitive among companies offering services from similar locations with similar vehicles.

With respect to ODM Aviation, this finding suggests two primary factors. First, if ODM services provide higher quality service than traditional vehicles (perhaps through access to more landing and pickup locations, for example), then they may be competitive even if they charge higher fares than conventional helicopter operators. Second, ODM service providers may have an opportunity to price differentiate themselves from competitors if they are able to create a geographically diverse service network and provide services at lower cost than companies currently operating routes in the area.

Table 15. Comparison of fare per passenger mile for L.A. region helicopter charter services.

| <b>Destination</b>       | <b>Orbic Air</b> | <b>Jetboy Helic.</b> | <b>Star Helic.</b> | <b>Average</b> |
|--------------------------|------------------|----------------------|--------------------|----------------|
| Coachella Music Festival | \$5.88           | -                    | \$6.31             | \$6.10         |
| LAX                      | \$17.78          | \$10.53              | -                  | \$14.16        |
| Santa Barbara            | \$7.53           | \$5.59               | \$6.47             | \$6.53         |
| San Diego                | \$6.07           | \$5.14               | \$8.88             | \$6.70         |
| Orange County            | \$9.49           | \$5.55               | \$8.59             | \$7.88         |
| Big Bear                 | \$6.42           | -                    | \$6.40             | \$6.41         |

2. Charter Range Price Impact: The cost per passenger mile for helicopter charters declined with increasing charter range in Table 14. Figure 24 displays this trend is especially prominent for Orbic Air which charged a high premium for some of their short distance charter flights. This trend is similar to current practices in other modes of transportation such as airlines, buses, or taxis, and reflects the reality that companies seek to recoup a set of fixed costs per trip that make short distance travel more expensive per mile. For longer distance trips companies are able to “spread” the fixed costs and reduce the per mile cost. An opportunity may therefore exist for ODM service providers to achieve a competitive advantage if they operate short distance missions at a reduced premium.

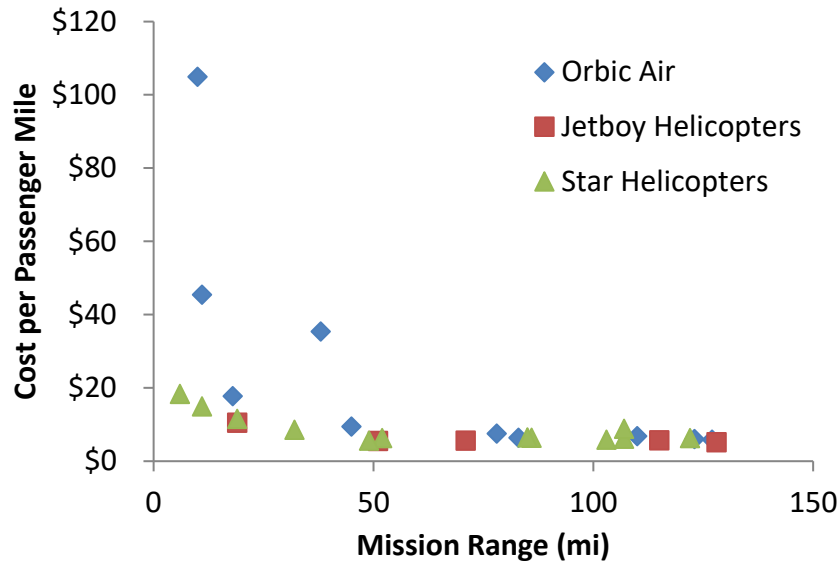


Figure 24. Cost per passenger mile versus helicopter charter flight mission range for three L.A. area service providers.

3. High Demand Services: There existed a significant cost differential between “routine” helicopter charter flights and “special event” flights in the current helicopter charter offerings. The three short range charter flights with costs per passenger mile greater than \$35 in Figure 24 correspond, in descending cost order, to flights to a Dodger Stadium baseball game, L.A. Live concert, and Angel Stadium baseball game. This trend suggests that there exists comparatively high demand and willingness to pay for helicopter flights to large events that routinely experience extreme ground traffic congestion. This may indicate a potential high value market for ODM Aviation. If the market exhibits high demand elasticity, then ODM Aviation may be able to significantly increase the number of individuals demanding this service by reducing the cost per passenger mile.
4. Price Adjustment for Round Trip: It may be seen in Table 14 that Orbic Air and Star Helicopters charged roughly the same fare for long distance charter services, despite the fact that Orbic Air provided a one-way flight while Star Helicopters provided a round trip. Furthermore, Star Helicopters charged the same fee for a round trip or one way flight for all its missions. This indicates that a significant portion of the current helicopter charter fare covers the non-revenue return flight, or “deadhead” flight.

ODM Aviation networks may have a competitive advantage if they are able to reduce the number or length of deadhead flights through increased passenger demand and the effective matching of passenger drop-off and new passenger pick-up locations. Numerous researchers have displayed the potential for advanced telematics to provide data that better optimizes network operations to reduce non-revenue mileage for ground vehicle ODM networks [47], [131], [132].

### 3.3.2 Consumer Demand for ODM Aviation to Replace Long Commutes

In addition to attracting customers currently purchasing helicopter charter flights, ODM Aviation is also proposed to appeal to individuals who currently endure long daily commutes [53]. Individuals experiencing long daily commutes may be classified into three categories [133]:

1. Extreme Commuters: Individuals who travel 90 minutes or more to work, one-way.
2. Long-Distance Commuters: Individuals who travel 50 miles or more to work, one-way.
3. Mega Commuters: Individuals who travel at least 50 miles over a time period of at least 90 minutes, one-way.

The U.S. Census Bureau found that roughly 5% of all U.S. full-time workers experienced one of these three categories of onerous daily commutes between 2006 and 2010 [133]. Decomposing this subset of the population into the three categories of long commuters, they found approximately 2.41% (1.7M individuals) to be extreme commuters, 3.15% (2.2M individuals) to be long-distance commuters, and 0.82% (587K individuals) to be mega commuters. If individuals with long commutes are assumed to have a higher likelihood of desiring cost effective ODM aircraft services, then up to 5% of the American population represents a potential early adopter market.

To support the L.A. basin case study, the number and geographic location of long commutes in Southern California was determined. The America 2050 initiative provided initial insight into the long commuter patterns of Southern California as summarized in Figure 25 [134]. In this figure, the Inland Empire (composed of Riverside and San Bernardino counties) is identified as the only major region in southern California where over 15% of the residents commute daily to a different region for work. While this does not directly indicate these individuals are experiencing long commutes, it does suggest that communities in the Inland Empire may be more likely to have long commutes. The U.S. Census Bureau's American Community Survey (ACS) identified two flows from the Inland Empire to Los Angeles confirming these predictions. Table 16 provides a ranking of the largest U.S. mega commuter routes ordered by the number of commuters; California mega commuter flows are highlighted in grey.

From Table 16 it is apparent that there are a significant number of individuals who engaged in daily mega commutes from the Inland Empire to Los Angeles County. Furthermore, the commuting routes from San Bernardino and Riverside counties actually ranked as the top two mega commuter routes in the United States by total number of participants. Interestingly, a second mega commuting route from Riverside County to San Diego appeared as the seventh most common mega commuting route. The remainder of Table 16 indicates that there are a significant number of mega commuters in and around New York City and the San Francisco Bay Area that should be considered as other potential high value markets; these were beyond the scope of this case study however.

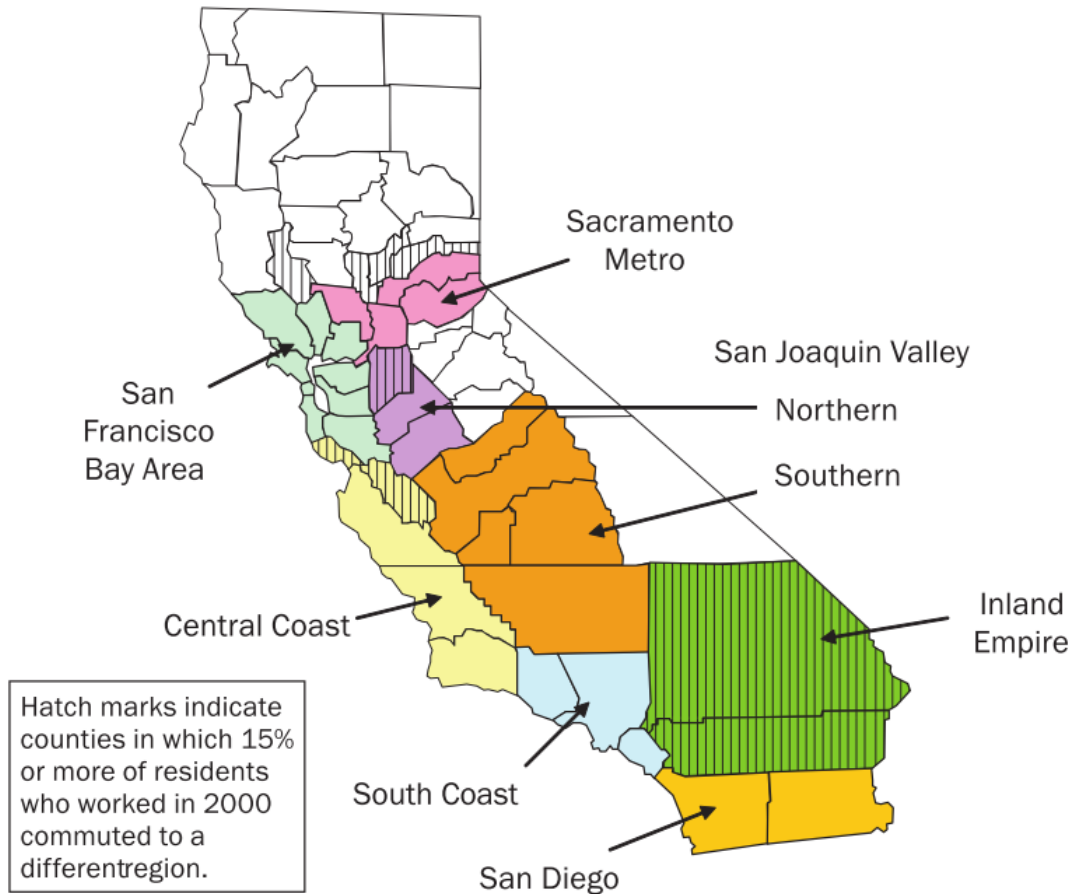


Figure 25. Commuter patterns between the regions of California determined from the 2000 U.S. Census Transportation Planning Package. *Image retrieved from the Healdsburg Research Seminar on Megaregions [134].*

Table 16. Mean travel time and distance for the top 10 U.S. mega commuter flows ranked by the number of participating commuters [133]. California commuter routes are indicated with grey shading.

| Origin                 | Work Destination    | Mean Commute   |                  |
|------------------------|---------------------|----------------|------------------|
|                        |                     | Time (minutes) | Distance (miles) |
| San Bernardino Co., CA | Los Angeles Co., CA | 104.2          | 68.0             |
| Riverside Co., CA      | Los Angeles Co., CA | 109.3          | 77.4             |
| Suffolk Co., NY        | New York Co., NY    | 114.2          | 64.5             |
| Fairfield Co., CT      | New York Co., NY    | 104.2          | 60.4             |
| Orange Co., NY         | New York Co., NY    | 110.7          | 62.3             |
| Mercer Co., NJ         | New York Co., NY    | 104.6          | 59.3             |
| Riverside Co., CA      | San Diego Co., CA   | 102.3          | 75.5             |
| Dutchess Co., NY       | New York Co., NY    | 116.8          | 76.3             |
| San Joaquin Co., CA    | Alameda Co., CA     | 104.1          | 61.5             |
| Monroe Co., PA         | New York Co., NY    | 120.5          | 91.1             |

Focusing on the mega commuter routes only within California, the potential magnitude of the market opportunity open to ODM Aviation was determined. Table 17 displays the number of individuals driving the most common mega commuter routes in California. Routes that reside within the L.A. basin case study system boundary are indicated with grey shading.

Table 17. Most common mega commuter routes in California [135]. Commuter routes within the L.A. basin case study system boundary are indicated with grey shading.

| <b>Origin</b>                        | <b>Work Destination</b> | <b>Mega Commuters</b> |
|--------------------------------------|-------------------------|-----------------------|
| Long Beach, Santa Ana                | Los Angeles County      | 75,800                |
| Oakland, Fremont                     | San Francisco County    | 46,234                |
| San Jose, Sunnyvale, Santa Clara     | San Francisco County    | 19,820                |
| Riverside, San Bernardino, Ontario   | Los Angeles County      | 15,816                |
| Carlsbad, San Marcos                 | San Diego County        | 14,036                |
| Sacramento, Arden, Arcade, Roseville | San Francisco County    | 8,044                 |
| Oxnard, Thousand Oaks, Ventura       | Los Angeles County      | 4,502                 |
| Bakersfield, Delano                  | Los Angeles County      | 2,758                 |
| Stockton                             | San Francisco County    | 2,360                 |

Interestingly, this data shows that the most common mega commuter route, with over 75,000 daily commuters, is from Long Beach and Santa Ana to Los Angeles. Furthermore, a variety of additional, lesser volume mega commuter flows into Los Angeles County such as from Bakersfield and Oxnard were also included. Figure 26 displays the set of mega commuter flows considered in this study. A subset of these were developed into reference missions in Chapter 4.

The existence of the mega commuter routes presented in Table 17 represents a clear market opportunity for an aircraft operator. Each day, thousands of individuals endure difficult commutes along these routes dedicating hours of time daily and tens of thousands of dollars annually to their transportation. While intra-urban ODM Aviation services offering transportation between any two points within a city have received a significant amount of attention from the media and emerging ODM providers, these mega commuting routes perhaps represent the lowest barrier to entry as new markets. The routes are relatively pre-defined between outlying communities and downtown areas, have a sizeable existing user base, and are well suited for service through a limited set of ground infrastructure nodes.

Considering these factors, mega-commuting routes present an array of potential opportunities and beneficial characteristics for new ODM operators. While low load factors for intra-city routes and utilizing a seat in the aircraft for the pilot are near-term business challenges for ODM operations, larger aircraft could be used for these long-distance commutes as customers could readily be pooled to provide a high load factor. In fact, the mega-commuter routes may represent logical market entry points for ODM operators to field-test new infrastructure, vehicles and business concepts on their way to provide intra-urban services with smaller vehicles serving a more geographically distributed ground infrastructure network. The review of long-distance reference missions further explored the opportunities for long-distance commuter and inter-city routes, as well as identified some of the unique challenges that arise for network balancing and vehicle operation.



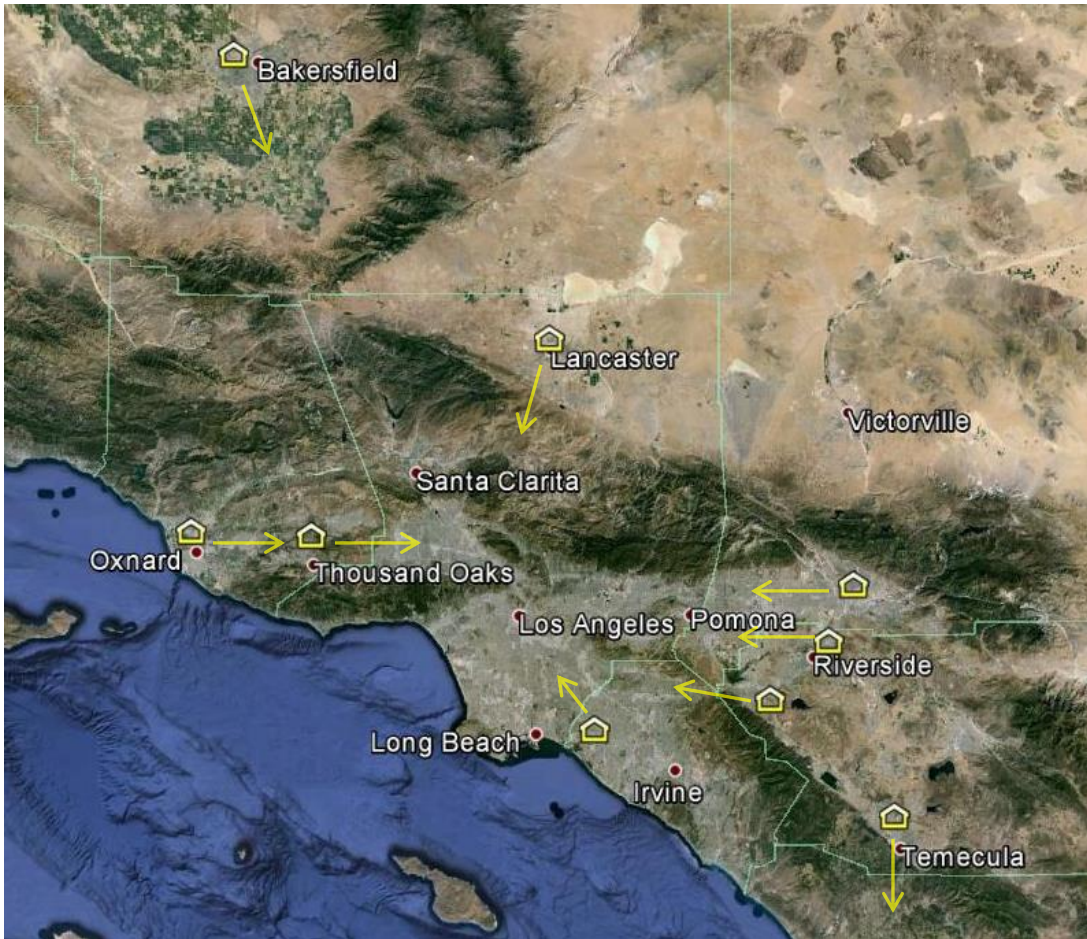


Figure 26. Common mega commuter routes into Los Angeles County and San Diego County. Yellow house pins designate approximate origin locations and yellow arrows indicate mega commuter flow direction.

© 2016 Google, © 2016 INEGI, Map Data: LDEO-Columbia, NSF, NOAA.

### 3.3.3 Consumer Demand for ODM Aviation from Wealthy Commuters

The third and final approach this research employed to identify promising early adopter ODM aircraft was to locate “high income commuter” communities in the L.A. basin. It was hypothesized that these communities may exhibit a greater willingness to pay for ODM aircraft services. The ACS and U.S. census data did not provide sufficient resolution of commuter income to effectively distinguish high income commuters in the mega commuter flows. Therefore, this research elected to use household income and home valuation estimations as proxies for commuter wealth.

Two methods were used to identify wealthy communities within the system boundary where high income commuters were assumed to originate from. First, the wealthiest neighborhoods in the system boundary were identified based upon the work of Stephen Highley. Highley used the 2006-2010 ACS data to determine contiguous census block groups (subdivisions of census tracts) that corresponded to neighborhoods with an average household income of over \$200,000 [136]. From his listing, 27 neighborhoods or groupings of neighborhoods were identified as potential wealthy commuter origin points.

Next, estimated home valuation information was reviewed from Trulia, a national real estate search and advertising site. These home valuations were used to confirm that Highley’s findings remained valid in 2016, as well as to identify additional neighborhoods with average home valuations of greater than one million dollars that could be considered as potential high income commuter areas. Figure 27 displays a property value heat map of the Los Angeles basin showing high income communities in purple. Through this second approach, an additional eight neighborhoods were added to the high income commuter list. This increased the total to 35 neighborhoods characterized as high income communities in this case study.

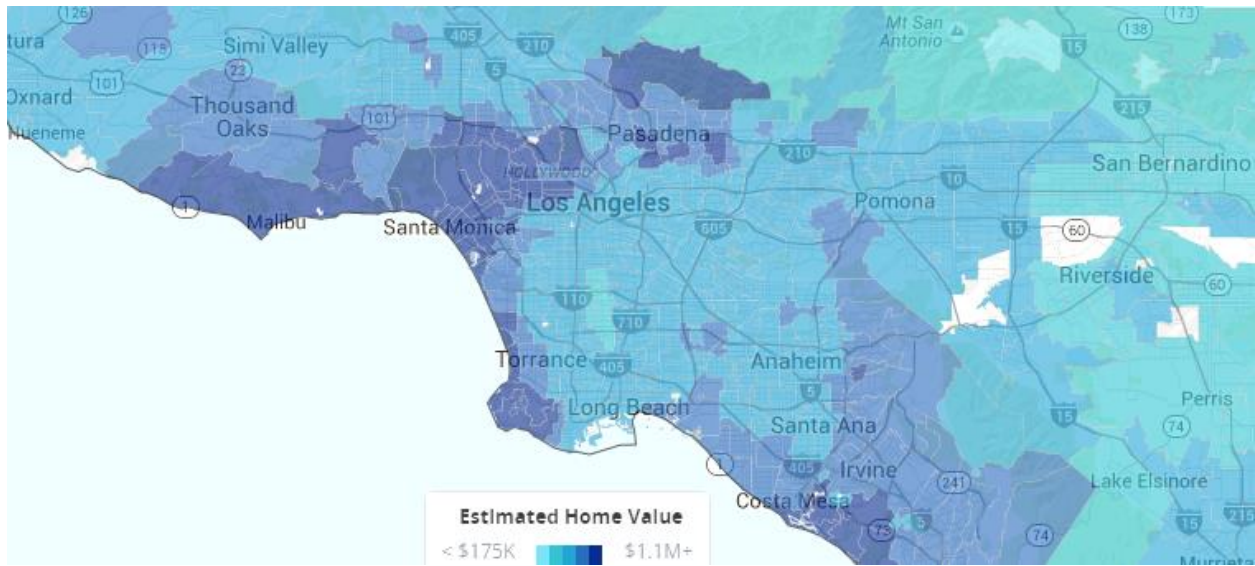


Figure 27. Estimated household valuation heat map of the Los Angeles basin showing high income communities in purple. *Image retrieved 7/17/2016 from www.trulia.com.*

Figure 28 displays the location of 35 high income neighborhoods as green house icons. These neighborhoods tended to be located on the perimeter of Los Angeles County either on the coastline or in the hills. It was interesting to note that the mega commuting areas (indicated with yellow house icons) reside for the most part on the west side of L.A. where there are few high income communities, or beyond the ring of high income communities. A subset of the high income commuter communities identified were developed into reference missions in Chapter 4.

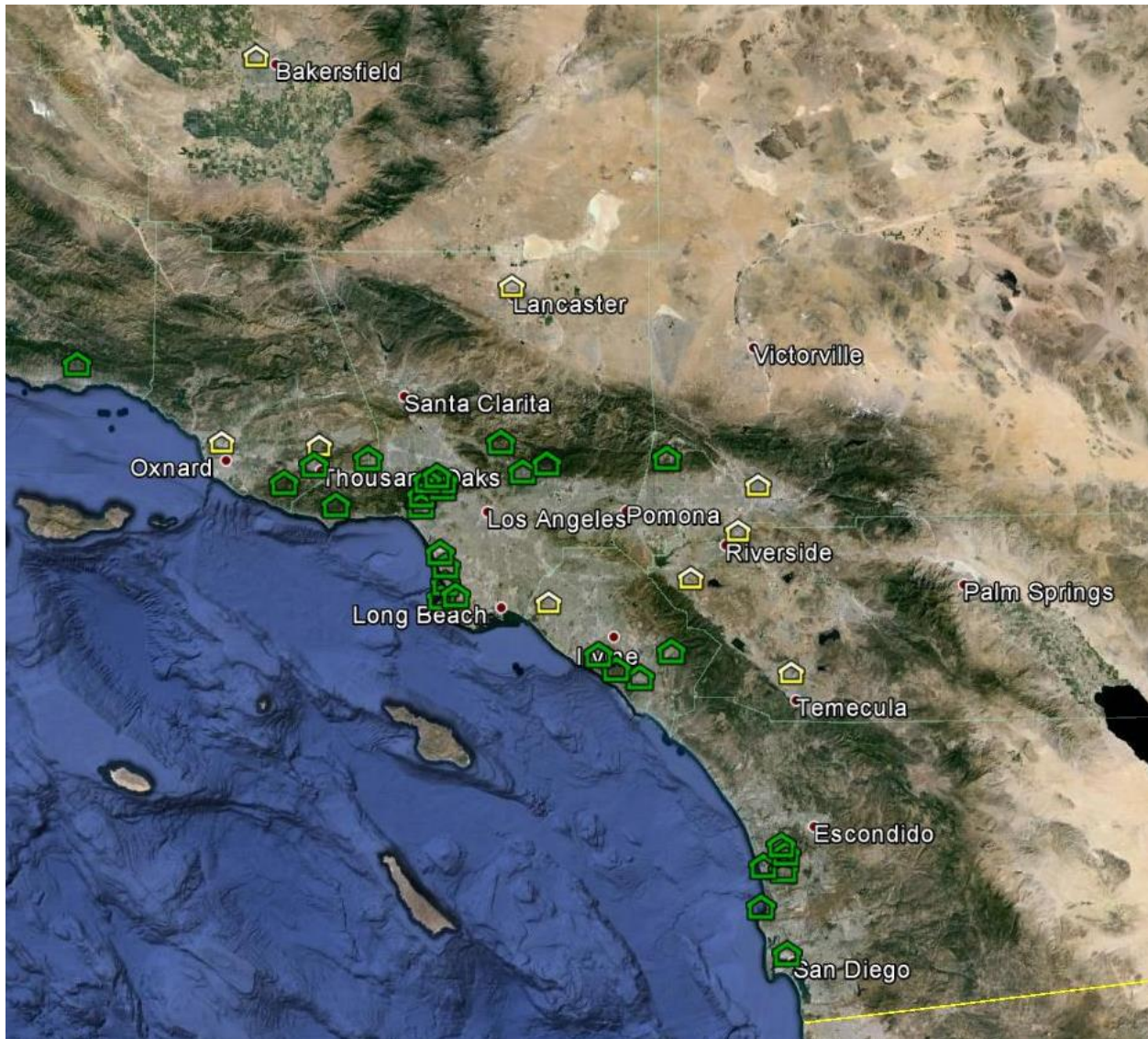


Figure 28. High income commuter (green icon) and mega commuter (yellow icon) communities within the L.A. basin case study system boundary.

© 2016 Google, © 2016 INEGI, Map Data: LDEO-Columbia, NSF, NOAA.

### ***3.4 Potential Enhancements to City Structure Enabled by ODM Aviation***

By recognizing the positive changes ODM Aviation may bring to city structure and transportation systems, operators may potentially leverage public funding and political support to bring about near-term infrastructure development and services.

The structure of cities, in terms of land-use and settlement patterns, is heavily dependent upon the geographic arrangement, quality and cost of the transportation systems that circulate people to, from and within the city. The field of urban planning is dedicated to the study of how city structure influences productivity, quality of life and sustainability, among other societal factors. Historically, urban planners have been restricted to automobiles and public transit modes as their primary transportation tools, however ODM Aviation offers dramatic new capabilities with *nodal*

versus *linear* transportation connections and may provide the means to support fundamentally new concepts in city planning.

Figure 29 displays a common structure for American metropolitan regions. Known as the “urban star,” the configuration is dominated by arms of dense urban development centered on high-capacity transportation lines, such as highways or railways, which radiate outwards from a central business district. In large metropolitan regions these corridors of development may terminate in another CBD or satellite city (indicated as “SC” in the figure). Beltway highways may also be constructed to connect adjacent arms [137].

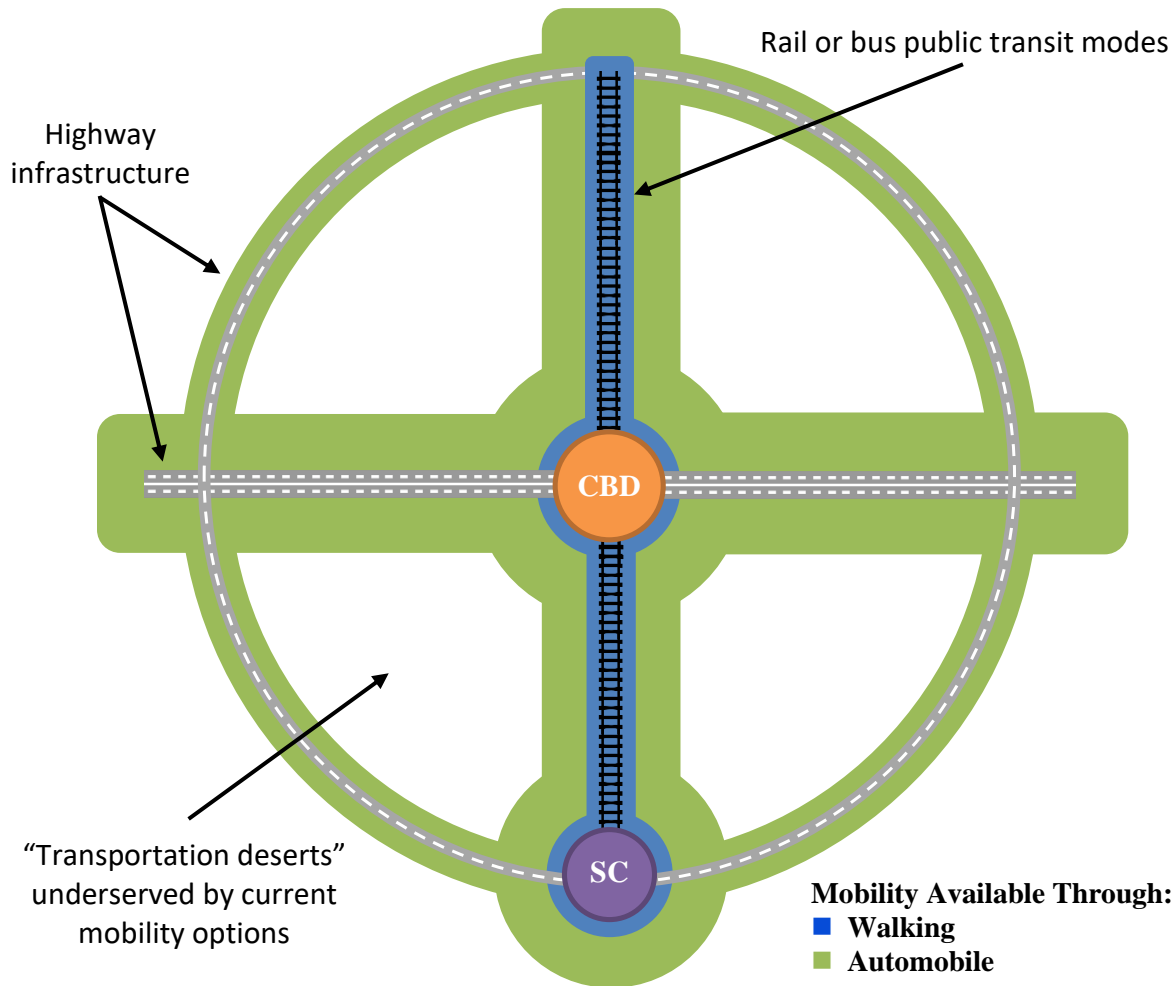


Figure 29. Notional diagram of an idealized “urban star” city structure indicating areas with efficient access to mobility provided through currently available surface transportation modes.

The color coded regions around the CBD and transportation infrastructure in Figure 29 notionally indicate the land area that has efficient access to mobility. Historically, the introduction of new transportation technologies has altered the location and percent of land connected to the CBD. Walking and animal-based modes only supported commuting to the CBD from the immediate surrounding areas. The development of the streetcar and metro created the first radial arms and enabled a dramatic expansion of land area that was connected to the urban core. The width of a

radial arm is commonly known as a “transit shed,” and indicates the area within which people will walk (or later drive) to reach the rail or bus line; experience has shown this distance to be roughly 400 meters when walking [138], [139].

The widespread adoption of the car again dramatically increased the land area with efficient access to the CBD. Additional radial arms sprung up around new highways, and beltways connected the arms providing access to previously underserved areas in between the arms. Furthermore, as cities grew in size and age, the transit and highway infrastructure became overburdened and often degraded. This created significant congestion that reduced the efficiency of transportation and again left many areas without sufficient access to high quality transportation. Finally, while travel to the CBD from any of the radial arms is quite efficient in the urban star, travel between the arms (especially through public transportation options) may be inefficient and require a circuitous routing through the CBD.

ODM Aviation has the potential to provide transportation capabilities dramatically different than current surface modes and to overcome some city structure challenges that resulted from these mobility deficits. Table 18 presents beneficial attributes of ODM Aviation that may enhance mobility in a metropolitan region. Figure 30 displays how mobility coverage in the urban star city structure may be enhanced through the implementation of ODM Aviation services.

Table 18. Operating attributes of aircraft that may influence mobility patterns and city structure.

| <b>Operating Attribute</b>     | <b>Capacity to Enhance Mobility in a Metropolitan Region</b>   |
|--------------------------------|--|
| Surface-Congestion Overflight  | Aircraft may overfly roadway congestion. This is especially beneficial during rush hour periods or in areas where geographic features create choke points, such as at bridges and tunnels.   |
| Geographic Obstacle Overflight | Aircraft may be able to overfly geographic obstacles such as mountains, bodies of water or parklands while surface-transportation modes must bypass or develop costly infrastructure to traverse these features.   |
| Increased Travel Speed         | NASA estimated the average speed of automobiles in metropolitan areas is 33 mph and the average speed of ODM aircraft as four times this rate [56]. The average travel time budget of a person is 1 to 1.5 hours per day [140]. This suggests ODM aviation may increase the reasonable daily commuter range from an average of 21 miles to as much as 100 miles. |
| Low Infrastructure Costs       | The relative cost of developing nodal infrastructure (helipads) for ODM aviation is low compared to linear infrastructure (highways and rail) for automobiles or trains.   |

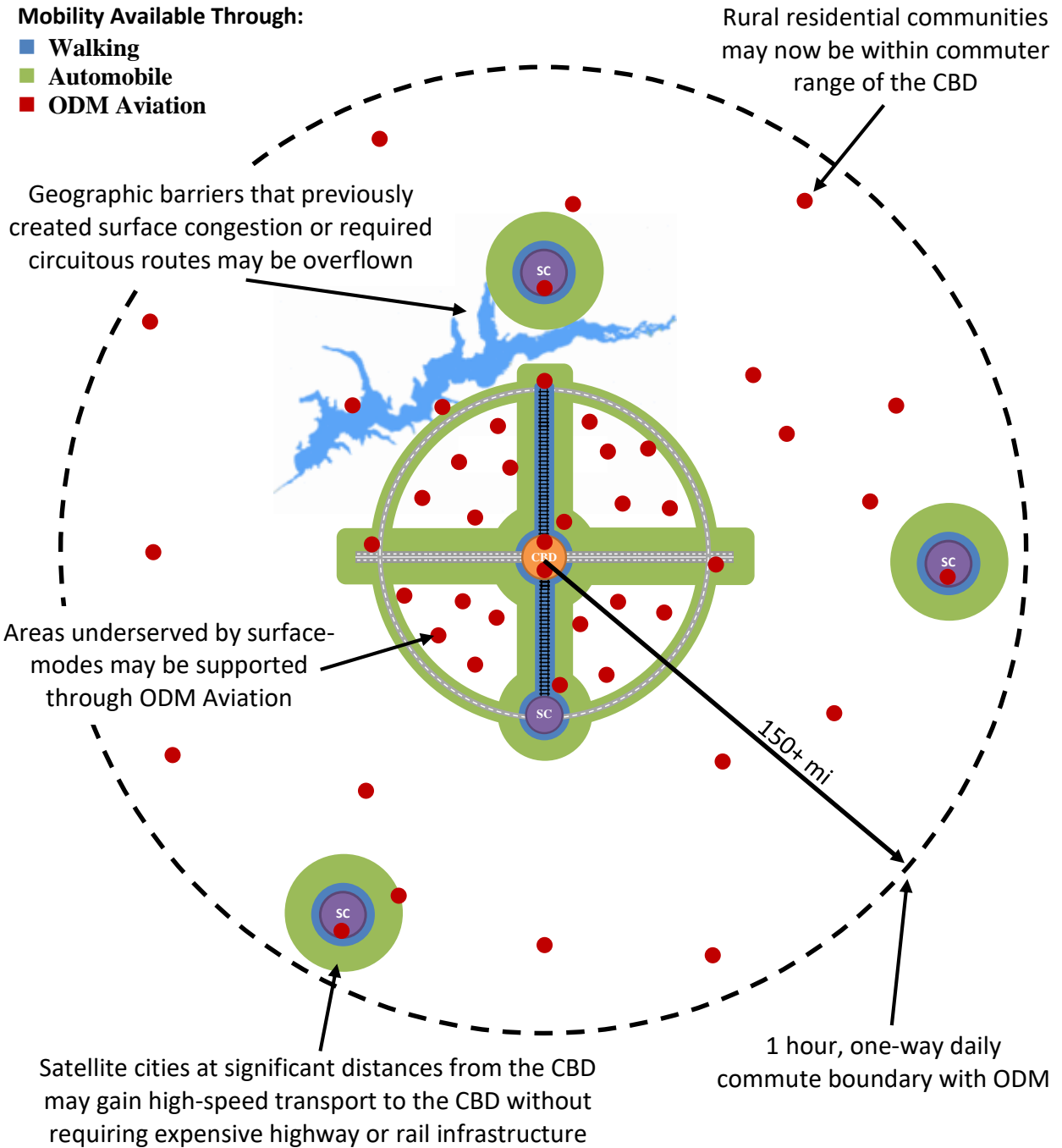


Figure 30. Concept of how ODM Aviation may influence mobility coverage in an urban star city structure by filling in the underserved spaces between the primary surface-mode branches and greatly expanding the feasible range of daily commuting into the CBD.

The capabilities of aircraft outlined in Table 18 constitute the primary competitive advantages of ODM Aviation. These factors are therefore likely to drive the routes and services that are pursued for near-term implementation. It should be noted that many of these benefits involve relatively long range flights to neighboring cities, new communities in previously rural areas, or communities at the edges of current surface transportation modes where commuters may experience severe congestion. These findings are consistent with the consumer demand markets identified for the Los Angeles region in Section 3.3. In contrast to these longer-range missions, ODM service to the underserved areas between the urban star arms represents a potential early-adopter market for short-range missions. These trends in early adopting markets supported the development and review of reference missions in Chapter 4.

Studying Figure 30, a variety of externalities were identified that may arise from city structure changes resulting from the adoption of ODM Aviation. The positive externalities represent opportunities for ODM Aviation to leverage to support near-term operations and are presented as potential market opportunities in the following sub-sections. The negative externalities, on the other hand, are considered potential risks to ODM Aviation that may impose operational challenges. The negative externalities are therefore presented within Chapter 5.

### **3.4.1 Increase Mobility to Communities Underserved by Surface Transportation**

*Transit deserts* are areas that lack adequate public transit services to meet the demand of “transit dependent” individuals residing within the area. The existence of such areas is a social equity concern as transit dependent populations are often composed of underprivileged individuals who are too young, old, poor, or otherwise physically disabled to drive [141, p. 1]. Transit deserts (or a broader consideration of *transportation deserts* where the highway and roadway access is also lacking) are also of concern to urban planners as they create stagnant regions in metropolitan area. Within transportation deserts land values remain low. Multi-generational poverty may also persist in these areas as a result of “spatial entrapment” where poor mobility prevents individuals from accessing distant jobs or healthcare, among other essential needs [142, pp. 37–44].

ODM Aviation may act as a mechanism to provide high quality mobility to communities that are currently underserved by highway or public transit infrastructure. The development of relatively low cost VTOL aircraft ground infrastructure in these communities can provide an access point to an aviation transportation network with direct linkages to areas and jobs that are otherwise difficult to reach from transportation deserts. ODM Aviation may therefore have the potential to reintegrate transit deserts into the overall city with minimal land-use change requirements and investment.

Beyond transportation deserts in metropolitan areas, some authors have suggested that new mobility modes (such as ODM Aviation) may reduce the difficulty of long distance commutes and enable middle and low income individuals to live in areas on the periphery of town where the cost of living is diminished [12], [90]. Many of the mega-commuter communities identified in Section 3.3.2 are indeed lower income areas where individuals may desire the transportation benefits provided by ODM Aviation.

These outcomes all represent positive externalities resulting from city structure changes due to ODM Aviation. As a result, there may be an opportunity to obtain public or private funding to support the development of ODM Aviation ground infrastructure in transportation deserts, and perhaps even subsidize the operation of flights to and from these areas.

### 3.4.2 Foster Regional Urbanization

While many urban and transportation planners hold the belief that revitalizing urban areas and creating more dense communities is the most beneficial route to reduce a variety of negative externalities associated with urban sprawl [96], [142], [143], some authors have also proposed that effective regional transportation planning may lead to “regional urbanization” through fundamentally different city structures that are inherently more equitable [115], [144] and more environmentally sustainable [145].

For example, the urban star city structure presented in Figure 29 inherently aggregates transportation resources, services, development and wealth in the CBD and along the radial arms. While ODM Aviation shows promise to better connect many of the underserved areas between the arms, equity challenges will likely persist with this city structure. An alternative city structure that has been proposed as fundamentally more sustainable and equitable is a polycentric network of smaller CBDs spread throughout a megaregion [137], [144]. Instead of a large CBD with long public transit or highway infrastructure ferrying people in from the suburbs and exurbs, the urban star city structure is replaced by a number of smaller towns that allow people to live within close commuting ranges.

The limiting challenge for polycentric city structures has historically been efficient transportation *between* the numerous CBDs. Los Angeles is currently the best example of a polycentric city in the United States. The L.A. region has 45 distinct urban employment centers while an average American city has  $8 \pm 2$  [146]. However, in part as a result of this city structure and in part because of the total population of the region, L.A. has some of the most severe roadway congestion in the world as individuals seek to travel between these multiple CBDs.

ODM Aviation may provide new capabilities to realize efficient regional urbanization by enabling high-speed connections, possibly without congestion, between spatially distributed urban employment centers. A polycentric city structure is inherently nodal, and therefore the nodal nature of ODM Aviation better matches the transportation needs of a polycentric city than the linear nature of ground infrastructure. Figure 31 notionally illustrates this concept by displaying that while only five aircraft ground infrastructure points would be required to connect five polycentric CBDs in a metropolitan region, ten highways (or railways) would be required to directly connect all CBDs to one another. In fact, any fully connected network would require  $n(n - 1)/2$  linear links where “n” is the number of nodes in the network.

While in reality a roadway is not built on the direct line of sight between every city in a region, but rather large artery roadways are used to connect multiple cities simultaneously, the benefit of the nodal nature of aviation are clearly apparent for polycentric city configurations. A potential city structure impact of ODM Aviation is therefore the ability provide rapid transportation between CBDs and enable polycentric megaregion development without the need for inordinately expensive infrastructure and land use changes. The resultant benefits of regional urbanization may therefore be considered a positive potential externality of ODM Aviation implementation. New ODM companies may be able to leverage this capability to receive public or private funding to develop ground infrastructure in city centers and conduct inter-city flights in a polycentric region.



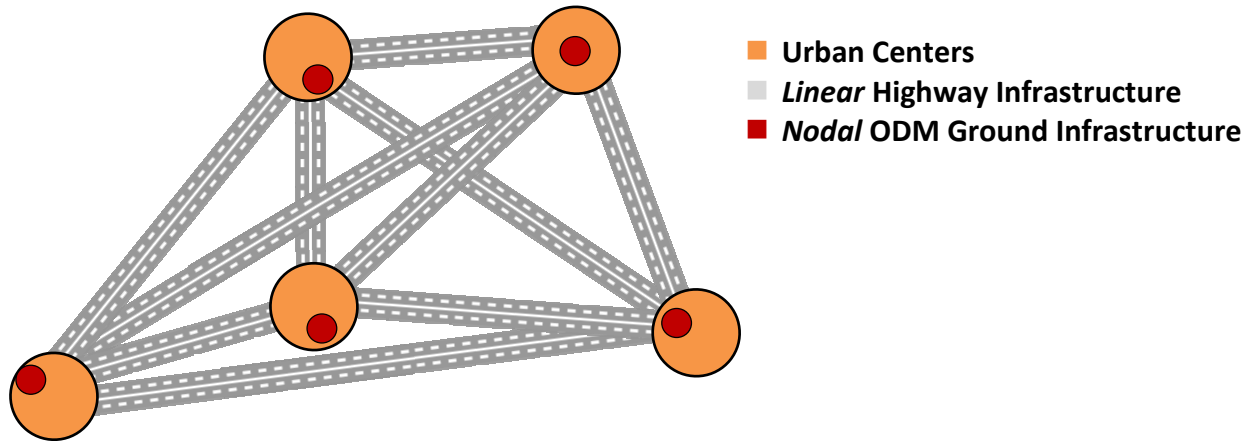


Figure 31. Nodal ODM Aviation ground infrastructure reduces the land usage and costs required to provide rapid inter-city connections compared to linear surface transportation infrastructure.

### 3.4.3 Co-Location of Ground Infrastructure with Consumers' Communities

Airports have frequently been focal points of environmental justice concerns as they may degrade the quality of life for nearby neighborhoods. Unlike current commercial aviation which concentrates customers at large hub airports, ODM customers will likely utilize ground infrastructure (similar to helipads) located within their own communities. This represents an opportunity not only for ODM Aviation to provide more convenient service, but also to avoid the community activism that has plagued large airports.

The co-location of ODM Aviation access points with the communities that use them internalizes some of the externalities from aircraft operations such as noise, light, vibrations and hazards created during takeoff and landing. Unfortunately, this line of reasoning breaks down when the generation of electricity to power the aircraft is considered. It is likely that the power plant facilities, even if renewable, will be located in communities other than those which are using the ODM Aviation services. The emissions, toxins, land usage and other negative externalities from the power generation may therefore still impact communities not benefiting from the service.

## 3.5 Opportunities to Increase Transportation Resiliency and Affordability

Nodal infrastructure is inherently more robust than linear infrastructure. For example, while congestion, a traffic accident or a natural disaster may only stop flow at a single point on a highway, the throughput of the overall road network may be significantly reduced or even stopped as traffic seeks alternative routes. In comparison, the closure of an ODM ground infrastructure point simply reduces network throughput to the immediate surrounding region, while the remainder of the network may operate optimally.

ODM Aviation may therefore provide more *reliable* mobility to any given community. This is especially critical in situations involving emergency medical services, public safety or disasters where ODM Aviation may provide or restore mobility capabilities more quickly. While increased reliability may be a significant competitive advantage of ODM Aviation, significant research must be conducted to identify how maintenance, scheduling and weather conditions may impact the operation of ODM aircraft services.

Furthermore, ODM aircraft will almost certainly be considerably more expensive to own and operate than even top-end luxury cars available today. Private aircraft ownership and utilization will therefore be beyond the means of most individuals and could lead to a host of social equity concerns; it could be perceived as if the wealthy have an essentially private transportation network. Due to the high costs and training requirements of aircraft operation, most ODM manufactures and transportation service providers anticipate ODM aircraft will be used to provide mobility as a service.

Mobility as a Service (MaaS) is a key aspect of the emerging “sharing economy” where expensive assets may be more efficiently utilized through services on the free market rather than in private ownership. Higher utilization drives down the total cost of operation and therefore allows the service to be provided at comparatively little cost compared to what is required to operate the vehicle privately. This “democratization” of transportation assets brings more affordable, high quality mobility to individuals who do not have the capital to privately own the asset [56].

Through the adoption of a MaaS business concept, ODM Aviation will likely have the positive social equity impact of making short-distance aviation services available to those who have previously been unable to afford general aviation or private charter aviation services. This represents a unique opportunity for ODM Aviation to penetrate a market that is insufficiently served by any other technology or provider.

### ***3.6 ODM Aviation Influence on Careers in Transportation Services***

A final opportunity related to a positive social equity externality is the potential impact of ODM Aviation services on the careers available in transportation services. The emergence of mobility as a service has generally been considered a boon for transportation employment and garnered support from local communities and governments. Transportation was dominated by the private car for the past century and private drivers internalized the cost of their trips by operating the vehicle themselves. However, transportation service providers such as Uber and Lyft have created millions of new driving jobs that are relatively accessible for low-education and low-income individuals.

In the near-term, ODM Aviation implementation may result in a similar positive externality and represent an opportunity to garner support for the industry. ODM Aviation operations will require investments in ground infrastructure construction, require the development and production of new aircraft, and stand up a network of mechanics, pilots, and security personnel, among others. These activities will all create fundamentally new jobs for both low and high skill-level individuals. Although most ODM flights will replace long distance private car trips, consumers are unlikely to forgo owning a car for general use for other short-distance missions. Therefore, the car sales, maintenance and cleaning industries are unlikely to see significantly reduced demand and employment as a result of ODM Aviation.

However, despite near-term benefits and opportunities, both the ODM Aviation and ODM car service markets face far-term social equity challenges. As discussed in Section 2.3.3, full automation is an important far-term goal for ODM businesses as it may significantly increase the profitability of their operations. While moderate automation in aviation may initially enable lower education individuals to obtain jobs as mechanics or pilots, the full automation of piloting features will remove a significant proportion of these jobs. Furthermore, if ODM Aviation grows to

significant scale in the long-term, then it may reduce the number of customers purchasing cars or using other forms of transportation such as trains and bus services. Cannibalizing these existing industries could result in the loss of significant numbers of low skill careers.

Despite this long-term challenge, ODM Aviation companies may leverage the near-term job-creation aspect of this industry to enter into some markets and cities.

### ***3.7 Opportunities to Reduce the Environmental Impact of Urban Transportation***

ODM Aviation may increase the environmental sustainability of a region's transportation system by specifically serving routes that currently require high-impact ground transportation travel, such as routes with significant surface congestion or routes that pass around geological features such as bodies of water. Re-moding these specific missions to aircraft could increase the overall sustainability of the entire transportation system. This concept may be thought of as optimizing a city's *mobility portfolio* with the goal of minimizing environmental impacts. With rising private and public scrutiny of environmental sustainability, ODM Aviation may realize large benefits by aligning initial markets and services with routes that reduce the environmental impact of transportation.

To identify the surface-transportation routes and missions that constitute ODM Aviation opportunities from an environmental sustainability standpoint, this research evaluated a set of basic scenarios where re-moding individuals to ODM aircraft may reduce the environmental impact of their travel. A first order emissions analysis was conducted for these scenarios to compare private car and ODM aircraft emissions.

To support this analysis a variety of operating assumptions were made. First, it was assumed that the average block speed for the private car was 33 mph (except in the scenario modeling congestion) and the average block speed for the ODM aircraft was 132 mph; these speeds are consistent with estimations used by NASA [56, p. 4].

Second, all five scenarios were simulated for an arbitrary 30 mile ODM aviation trip with either two or four passengers. The first order electric aircraft performance model developed in Section 2.3.1.1 was used to determine the in-flight energy required to fly the mission. The total CO<sub>2</sub> emissions of the flight were then estimated for electric aircraft through the process developed in Section 2.3.1.3.

A third assumption was that the required electricity came from a grid with the average U.S. electricity generation resource mix. It should be noted that additional energy required during climb, maneuvering, and descent were neglected in this model.

The CO<sub>2</sub> emissions from the operation of a private car were calculated for scenarios without congestion by estimating the emissions per mile for an average American private vehicle. The average fuel efficiency for private cars in the U.S. in 2014 was 23.2 miles per gallon (MPG) [147]. The U.S. EPA estimates a gallon of gasoline emits 8,887 grams of CO<sub>2</sub> when burned. Dividing the CO<sub>2</sub> emission per gallon by the fuel efficiency of the vehicle provides an estimate of 383 grams of CO<sub>2</sub> emitted per mile by the average American car.

This estimation will *overestimate* the emissions of private cars when ODM aircraft enter the market because vehicle fuel efficiency standards require 42 MPG by 2020 and 54.5 MPG by 2025 which will raise the average fuel efficiency of the total fleet. However, the overestimation was deemed acceptable for this first order *comparative* analysis as the average MPG of the overall U.S. private care fleet will rise slowly (no more than a few MPG per decade), and the electrical generation portfolio is also likely to include more renewables (also not modeled in this analysis) which would simultaneously reduce the CO<sub>2</sub> emissions for the aircraft.

Finally, estimating the CO<sub>2</sub> emissions from private cars in the scenario considering congestion was more involved. First, the average vehicle speed was found for each congestion area based upon the speed penalty applied. Second, an emissions-speed curve developed by the University of California Transportation Center was used to determine the vehicle CO<sub>2</sub> emissions per mile for these vehicle speeds [148]. The emissions-speed curve was based upon a vehicle data set with a mode of 26 MPG. In order to make the curve consistent with the chosen average MPG of 23.3 for this analysis, 41.2 gCO<sub>2</sub>/mile was added to all estimations from the curve. The total CO<sub>2</sub> emissions from the complete trip were then estimated by summing the emissions produced in each congestion area.

Figure 32 presents the baseline comparison case where both the ODM aircraft and private car travel the same distance routes with no congestion and one passenger each (including a pilot for the aircraft). As may be seen, although the aircraft completes the journey in less than half the time, the private car performs better from an emissions standpoint (though only moderately). This baseline case displays how ODM Aviation could trigger environmental concerns and face potential operating challenges from state or national emissions reductions goals when compared with automobiles for standard routes. The difference would be especially pronounced if modern high-efficiency or electric vehicles were considered instead of the fleet average vehicle.

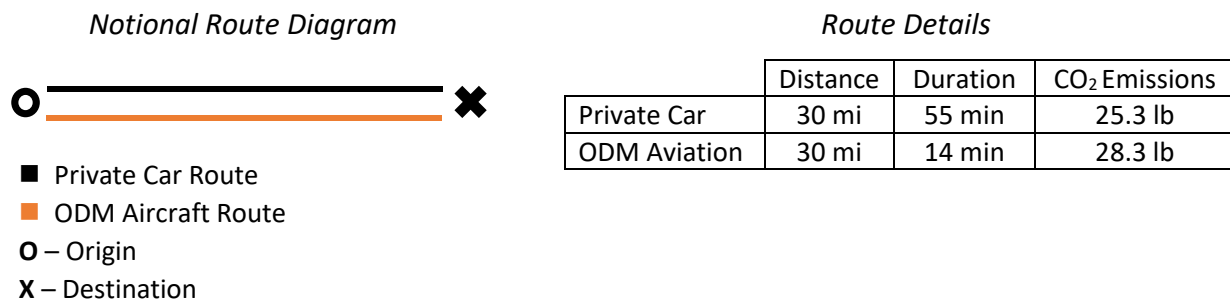


Figure 32. Comparison of car and aircraft operations for identical routes in ideal conditions.

Table 19, on the other hand, presents the set of scenarios where re-moding to ODM Aviation is likely to reduce environmental impacts. Furthermore, each scenario is visually represented in a figure that also displays the results of a first order CO<sub>2</sub> emissions analysis.

Table 19. Travel scenarios where ODM aircraft reduce environmental impacts compared to cars.

| <b>Scenario</b>  | <b>Description</b>  |
|--|---|
| Severe surface congestion<br>(Figure 33)                     | Although aircraft are more energy intense and result in greater environmental impacts per passenger kilometer than automobiles for ideal operating conditions, surface roadway congestion often increases the duration of travel by car many-fold during rush hour periods. In such cases it is possible the overall environmental impact of completing the trip through ODM Aviation (which does not experience congestion) is less than that of the car stuck in traffic. Note, however, that electric automobiles more or less negate this environmental advantage of aircraft as they are nearly equally efficient at high and low speeds.          |
| Circuitous surface route<br>(Figure 34)                      | Aircraft may be more environmentally friendly despite their higher energy intensity if they may complete the same mission by a significantly shorter route than automobiles. This scenario is likely to occur where roads must pass around natural geographical features such as mountains and bodies of water while aircraft may fly a much shorter path over them.  |
| High route demand<br>enables customer pooling<br>(Figure 35) | For routes where there are a significant number of people traveling from the same origin point to the same or nearby destination points, ODM Aviation may be able to “pool” customers. Higher aircraft load factors have the dual benefit of reducing the fare per customer as well as reducing the environmental impact per customer. Therefore, on routes where pooling is possible, a 4 seater ODM aircraft may be able to accommodate 3 passengers and therefore remove as many as 3 cars from the roadway. In this case it is likely the overall environmental impacts of the aircraft will be less than the combined impacts from the three cars. |
| Low noise flight<br>trajectories available<br>(Figure 36)    | Highway and roadway traffic places significant environmental burdens upon the communities through which they pass. These burdens include noise, emissions and safety concerns, among others. ODM Aviation may provide environmental justice benefits if it can transport customers by an alternative, low noise route that does not influence these communities. This may include flight over water or flight diffusion over less sensitive communities.  |

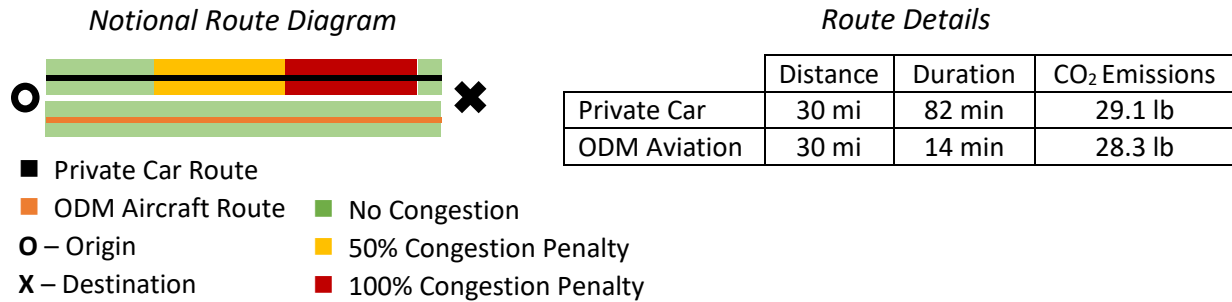


Figure 33. Comparison of private car and ODM aircraft operations for identical routes with surface congestion.

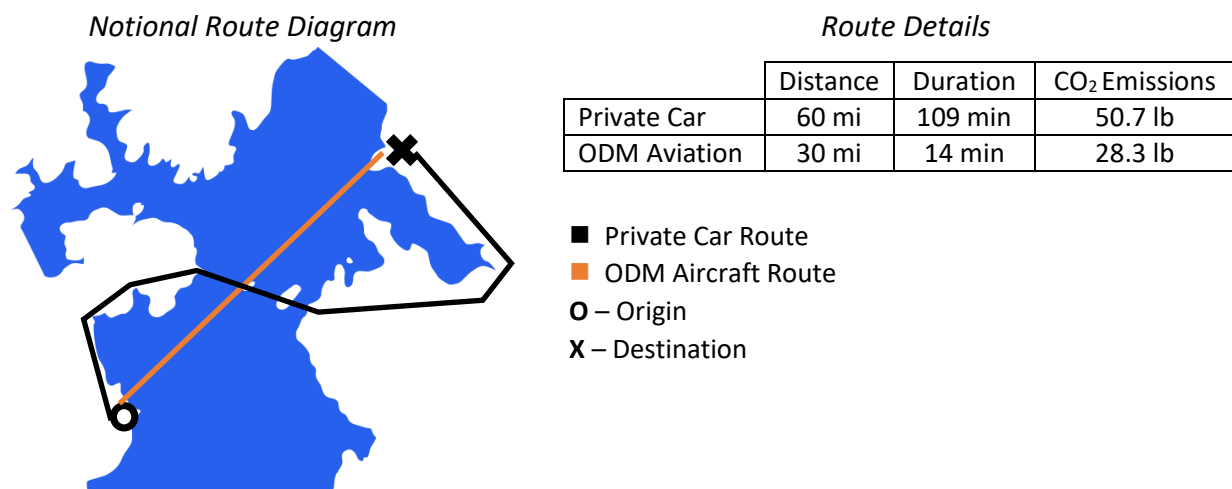


Figure 34. Comparison of private car and ODM aircraft operations for scenario with a circuitous surface route and straight line airborne route.

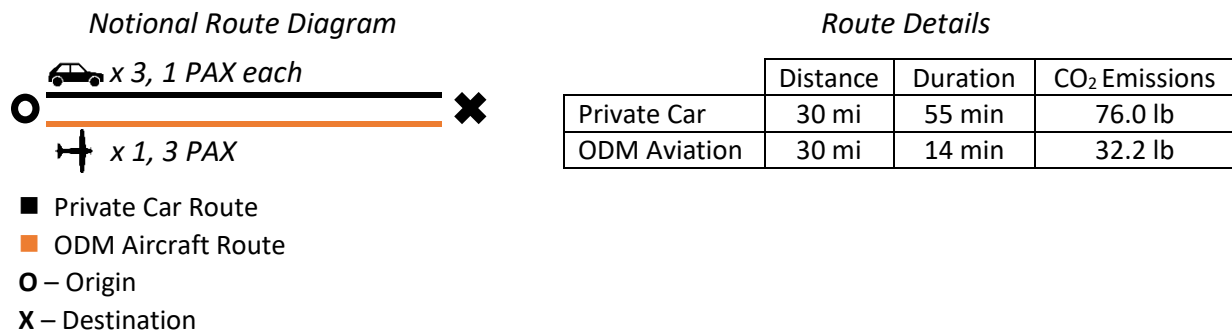


Figure 35. Comparison of operations for an aircraft with a high load factor and three private cars moving the same number of passengers on an identical route.

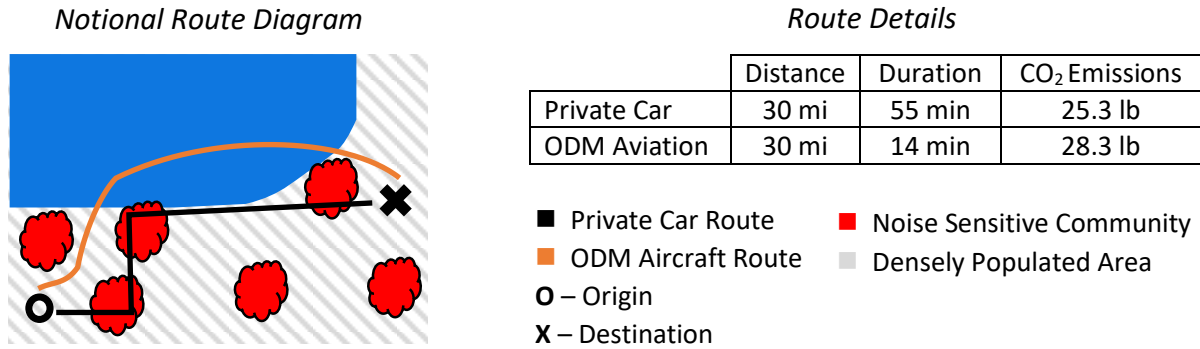


Figure 36. Comparison of private car and ODM aircraft operations with different routes through densely populated areas and noise sensitive communities.

Reviewing Table 19 and its accompanying figures, a variety of key factors were discerned that profoundly influence the environmental sustainability of ODM Aviation. For ODM Aviation to be more sustainable than transportation by private car, it is likely that ODM operators will have to achieve a majority of these factors. Table 20 presents the three key operation factors for the environmental impacts of ODM aircraft flight. These factors were taken into consideration during the design of reference missions in Chapter 4.

Table 20. Key operating factors that influence the environmental impact of aircraft operation.

| Operating Factor | Description   |
|------------------|---|
| Load factor      | Airlines have historically had a higher average load factor than any other mode of transportation. Reducing the environmental impacts of ODM Aviation compared to private automobiles will in most cases rely upon achieving high load factors.   |
| Demand balancing | Private vehicles have the advantage of being pre-located near the origin point of a customer’s mission. On the other hand, ODM vehicles (cars and aircraft) often must make a “ferrying” trip from a staging area to the origin point. In some cases this may more than double the overall distance of the mission and accrue significant additional environmental impacts. The length of the ferrying trip is minimized when the previous mission is terminated near the origin point of the new mission. This challenge is especially pronounced during rush hour periods where travel demand is heavily <i>directional</i> with nearly all people traveling in the same direction. Demand balancing and ferrying trips may be a considerable challenge for the sustainability of ODM Aviation. |
| Routing          | Aircraft routing and flight trajectory directly influences the energy requirement of the mission and the areas overflown. These factors in turn determine the environmental impacts of the mission. To minimize these impacts, aircraft should be routed via the lowest energy route (often shortest, lowest altitude) that avoids low altitude overflight of sensitive communities. Aircraft routing is constrained by airspaces, ATC and demand, among other factors.   |





## 4 Los Angeles Case Study Reference Mission Definition

The previous chapter outlined the first two steps of the case study in the L.A. basin; these were to define a system boundary for ODM Aviation operations and then estimate the consumer demand and geographic location of this demand. Chapter 4 introduces the third step of the case study by defining 12 ODM aircraft reference missions for which operational ConOps may be developed and analyzed. The 12 reference missions of this case study were developed to capture a wide diversity of potential ODM Aviation missions in the Los Angeles basin. The missions represent multiple types of markets, flights of diverse range, duration, demand and airspace congestion, access to varying levels of ground infrastructure, and diverse requirements for flight profiles.

While nine of the reference missions were specifically selected to represent anticipated early adopting markets, three of the reference missions were derived from randomly selected origin and destination points. The purpose of these three randomly selected reference missions was to reveal unidentified challenges or opportunities for the operation of ODM Aviation networks that may not have appeared in the reference missions defined solely based on the perceived initially promising markets. Figure 37 displays the different pathways through which these two categories of reference missions were developed. The analysis steps reviewed in this chapter are outlined in red.

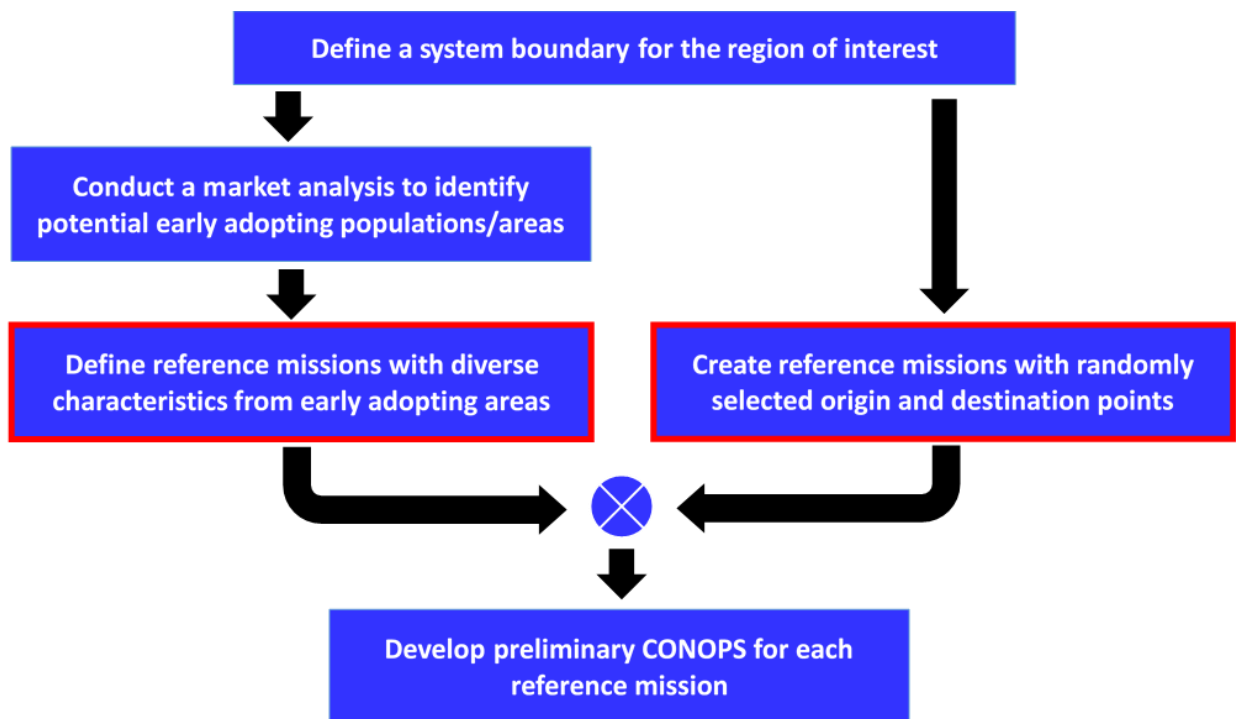


Figure 37. First principles approach to develop a set of ODM Aviation reference missions.

As shown in Figure 37, the three likely early adopter ODM aircraft service markets introduced in Section 3.3 (current helicopter charter routes, mega commuter routes, and high income commuter routes) were used as a foundation to define nine reference missions. These nine missions cover a diverse range of potential consumer needs and mission requirements from both the daily commute and non-commute point-to-point mission categories. The twelve reference missions defined in this chapter are summarized in Table 21.

Table 21. Summary and characteristics of the 12 reference missions.

| Mission Category           | Mission Characteristic                              | Mission Origin and Destination Points                          |
|----------------------------|---|--|
| Daily Commute Missions     | Wealthy Commuter                                    | 1. Malibu → Century City                                       |
|                            | Mega Commuter                                       | 2. San Bernardino → Glendale City Center                       |
| Point to Point Missions    | Inter-City  | 3. Antelope Valley → L.A. City Center                          |
|                            |   | 4. San Diego City Center → L.A. City Center                    |
|                            | Intra-City  | 5. L.A. City Center → Long Beach City Beach                    |
|                            |   | 6. The Beverly Hills Hotel → Los Angeles International Airport |
|                            |   | 7. Redondo Beach → Dodger Stadium                              |
|                            | 8. Rancho Palos Verdes → Torrance Memorial Hospital |  |
| Recreation                 | 9. San Marino → Palm Springs                        |  |
| Randomly Selected Missions | -   | 10. San Bernardino → Perris                                    |
|                            |   | 11. Arleta → Corona  |
|                            |   | 12. Altadena → Culver City                                     |

#### 4.1 Reference Mission Definition Approach

The first step to defining the reference missions was to choose origin and destination points for the potential ODM aircraft services. These were selected based upon the three likely early adopter markets introduced in Section 3.3. A representative address was selected within the general origin region (such as in a neighborhood), and the address of the destination was also determined. Nine reference missions were defined to collectively represent the diversity of potential ODM operational requirements. The reference missions included long distance mega commuting routes, short distance wealthy commuter travel, medical emergency travel and recreational travel, among others.

While some researchers have stochastically simulated hundreds to thousands of potential missions for early-phase conceptual design, this research approach prioritized minimizing the number of missions (and therefore the complexity of the analysis). By strategically selecting a small set of missions that exhibited the range of possible characteristics, then the same results could theoretically be found with far fewer samples. This research approach therefore put greater focus into deriving a representative set of reference missions from first principles on the front end, rather than spending many more resources on the back end of the analysis to evaluate far more samples.

The validity of the daily commuter reference mission origin and destination points was confirmed through the use of the U.S. Census Bureau Longitudinal Employer-Household Dynamics Origin-Destination Employment Statistics (LODES) 2014 data sets. The LODES data was used to develop a “laborshed” mapping for the reference mission origin area. A laborshed is typically a heat map that displays where workers in a specified employment reference area commute from to get to work. However, for the case of this study the *inverse* laborshed is of interest to reveal where individuals that reside in a specified area of residence commute to work. Laborshed mappings may

be likened to the concept of a watershed. It should be noted that the LODES data does not capture the current commuting pattern of every individual living in an area, and therefore the laborshed mappings developed should not be considered as precise market estimations.

This research identified potential early adopter ODM aircraft service markets based upon place of residence and relative wealth of that residence. Therefore, by developing an inverse laborshed mapping that identified where individuals from these communities commute to for work, the number of commuters that travel from the chosen reference mission origin area to the chosen destination point was determined.

The identification of actual commuter patterns verified that the reference missions represented real markets, and quantified the magnitude of the potential demand for the reference missions. Furthermore, the inverse laborshed mapping in some cases revealed other “hot spots” where a large number of individuals from the community of interest commuted to for work. These hot spots may represent other promising high value missions for ODM Aviation services. These studies were only conducted for the daily commuter missions as the LODES data provided no information on non-commute point-to-point travel.

Next, a ground transportation study was conducted for each reference mission. This study determined the travel time profile for a reference mission if it were to be completed through the use of an automobile (private or commercial). In order to develop this travel profile, the Google Maps™ mapping service travel predictions were queried for a single route over the course of a representative day. The results from these queries created an impression of the severity of ground congestion along the reference routes and provided insight into the time dependency of ODM Aviation demand patterns.

The Google Maps™ mapping service has access to a wealth of commuter and point-to-point travel information through GPS tracking. The maps use sophisticated travel prediction algorithms that draw upon official speed limits, recommended speeds, likely speeds based on road type, historical average speed data (adjusted for time and day), actual travel time from users, and real-time traffic information [149]. Therefore, this tool was assumed to be adequate to develop travel time profiles of sufficient accuracy for this case study. Future studies may seek to develop more accurate travel time profiles and route mappings through the use of aggregated cell phone tracking data, such as shown by [150] and [151].

Through a sensitivity study that sampled each day of the week for multiple weeks throughout the year, it was determined that weekend traffic (inclusive of Friday) tended to be the most severe and often exhibited a different travel time profile than the standard weekday profile. Although each day of the week had a slightly different travel time profile, travel predictions for Tuesdays appeared to be roughly the mean of the standard weekday travel patterns. Therefore, Tuesday May 17, 2016 was selected as the representative day for this case study, and the reference mission travel time profiles were developed through the Google Maps™ mapping service travel predictions for this day. Future studies may create more comprehensive travel time profiles by considering an entire week and samples from multiple times of the year.

As an additional note, the Google Maps™ mapping service presented only aggregate data. While this was ideal to estimate daily commute references missions (albeit it did not capture variance in

congestion due to road conditions such as major accidents or construction), it did not accurately represent the traffic that an individual may expect to encounter for point-to-point travel to non-recurring events such as sporting events. Therefore the travel time profiles presented for the point-to-point reference missions that involve non-recurring events should be viewed as lower bound estimates of travel time as there was likely to be significant additional event congestion.

The final step of the reference mission definition was to identify existing potential takeoff and landing locations for the ODM aircraft. For this analysis, viable current day takeoff and landing locations were considered to have the following traits:

- Must be designated as either helicopter landing facilities or airports
- Must not be reserved for medical use, such as hospital landing facilities
- May be an emergency helicopter landing facility. *Note these facilities are not approved for commercial operations at this time. It was assumed they could be viable facilities in the near future*
- May be a public service helipad, such as a police or firefighter facility, so long as it is not contained within a secure, access controlled facility such as a prison or police station
- May be a private facility, even a facility located in a private compound or rooftop

## **4.2 Daily Commute Reference Missions**

As a reminder, the daily commuter mission type covered situations where an aircraft is utilized during business days to transport individuals between a location near their place of residence to a location near their place of work, and vice-versa. This research proposed that the early adopter daily commute markets will likely be where individuals experience long commutes, such as those identified in Section 3.3.2, or routes where individuals with high income travel, such as those identified in Section 3.3.3. Three reference missions were defined that characterized the array of possible needs, operational challenges and opportunities ODM daily commuter aircraft services may face. The Malibu to Century City reference mission is developed in detail below. The other two daily commute reference missions are also briefly introduced. For the sake of brevity the detailed development of these other two references missions is presented in Appendix A.

### **4.2.1 Malibu to Century City Reference Mission**

The Malibu to Century City reference mission captures a potential wealthy commuter market with a ground transportation “choke point.” Malibu is an affluent coastal town west of Los Angeles. Century City is a significant business and cultural satellite city west of Los Angeles and roughly 27 miles east of Malibu. Shown as a purple line in Figure 38, the primary route from Malibu to Century City is to drive the highway 1 on the coast. The primary alternative route passes through the Santa Monica Mountains to highway 101 and nearly doubles the trip distance. As a result, highway 1, which has only two lanes in each direction, acts as a choke point that becomes significantly congested during peak traffic periods. Although the reference mission is only 27.5 miles and 40 minutes during low traffic periods, it may take as long as 110 minutes during peak weekday commuting periods; this represents a 175% congestion penalty. The route is therefore considered an “extreme commute” during peak congestion periods.

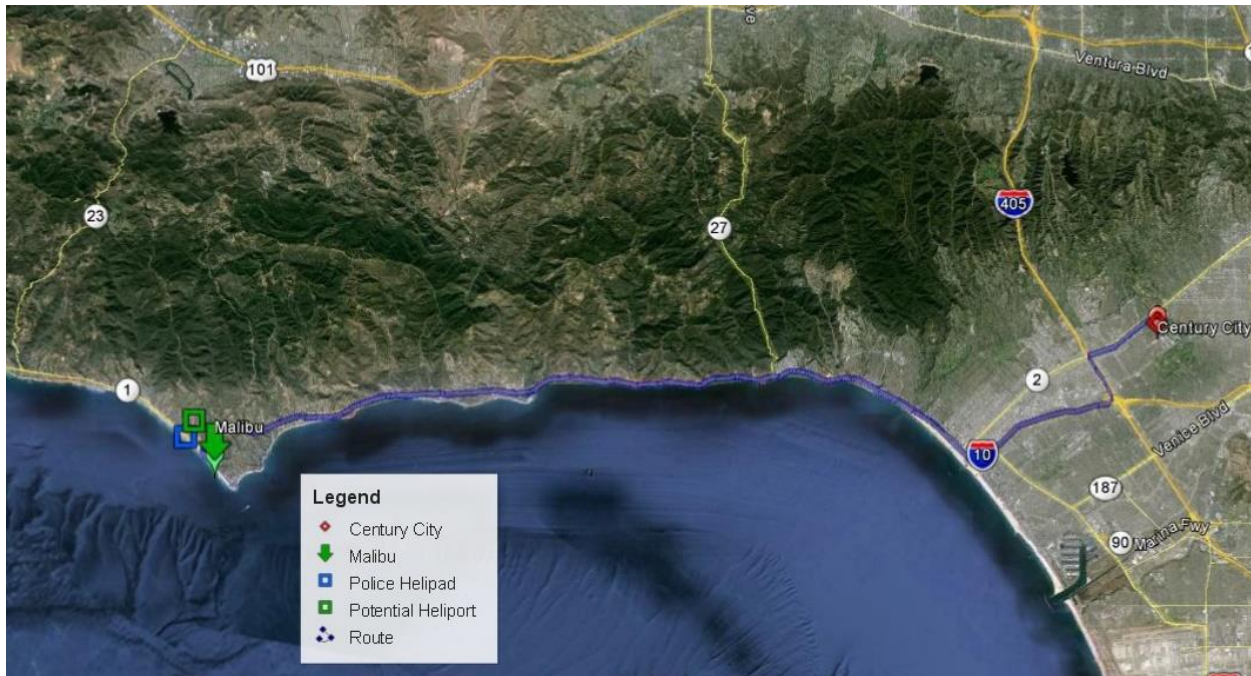


Figure 38. Malibu to Century City reference mission.

© 2016 Google, Map Data: SIO, NOAA, U.S. Navy, NGA, GEBCO, USGS.

Table 22 displays the specifications for the Malibu to Century City reference mission. The mission origin point was chosen within one of the highest value neighborhoods along the coast. The nearest existing helipad is a police surface facility located on the beach 1.3 miles from the mission origin point. The police helipad is not located in a secured facility and therefore was assumed in this analysis as accessible for ODM aircraft operations. The mission destination point is an office building in Century City with an onsite helipad.

Table 22. Malibu to Century City reference mission specifications.

|                             |   |                   |      |                     |
|-----------------------------|---|-------------------|------|---------------------|
| <b>Type:</b>                | Wealthy Commuter, Extreme Commute, Choke Point                |                   |      |                     |
| <b>Origin:</b>              | 7006 Birdview Ave, Malibu, CA 90265                           |                   |      |                     |
| <b>2016 Origin Helipad:</b> | L.A. Police Helipad: 5 Zuma Beach Access Rd, Malibu, CA 90265 |                   |      |                     |
| <b>Destination:</b>         | Century City: 1901 Avenue of the Stars, Los Angeles, CA 90067 |                   |      |                     |
| <b>Destination Helipad:</b> | on-site   |                   |      |                     |
| <b>Driving Distance:</b>    | 27.5  | mi primary ground | 42.5 | mi secondary ground |
| <b>2016 ODM Distance:</b>   | 1.3   | mi to helipad     | 23.5 | mi LOS flight       |

Table 23 presents the ground transportation study for the Malibu to Century City reference mission. Ground transportation commuting times as predicted by the Google Maps™ mapping service were collected from 5:00 AM until 12:00 PM inbound from Malibu to Century City, and from 1:00 PM until 8:00 PM outbound from Century City to Malibu. The low and high travel time bound estimates were recorded, and an average time was estimated along with the half range plus or minus value. Finally, the average speed of travel for the entire ground transportation mission was estimated by dividing the primary ground route distance by the average trip duration.

Table 23. Malibu to Century City reference mission ground transportation study.

|          |           | Travel Time (minutes) |      |         |      | Avg. Speed (MPH) |    |
|----------|-----------|-----------------------|------|---------|------|------------------|----|
| Date     | Time      | Low                   | High | Average | +/-  |                  |    |
| Inbound  | 5/17/2016 | 5:00                  | 40   | 50      | 45   | 5                | 37 |
|          | 5/17/2016 | 6:00                  | 40   | 55      | 47.5 | 7.5              | 35 |
|          | 5/17/2016 | 7:00                  | 45   | 85      | 65   | 20               | 25 |
|          | 5/17/2016 | 8:00                  | 55   | 110     | 82.5 | 27.5             | 20 |
|          | 5/17/2016 | 9:00                  | 50   | 90      | 70   | 20               | 24 |
|          | 5/17/2016 | 10:00                 | 45   | 75      | 60   | 15               | 28 |
|          | 5/17/2016 | 11:00                 | 45   | 75      | 60   | 15               | 28 |
|          | 5/17/2016 | 12:00                 | 45   | 75      | 60   | 15               | 28 |
| Outbound | 5/17/2016 | 13:00                 | 45   | 75      | 60   | 15               | 28 |
|          | 5/17/2016 | 14:00                 | 45   | 75      | 60   | 15               | 28 |
|          | 5/17/2016 | 15:00                 | 45   | 80      | 62.5 | 17.5             | 26 |
|          | 5/17/2016 | 16:00                 | 45   | 90      | 67.5 | 22.5             | 24 |
|          | 5/17/2016 | 17:00                 | 50   | 100     | 75   | 25               | 22 |
|          | 5/17/2016 | 18:00                 | 50   | 85      | 67.5 | 17.5             | 24 |
|          | 5/17/2016 | 19:00                 | 45   | 65      | 55   | 10               | 30 |
|          | 5/17/2016 | 20:00                 | 40   | 60      | 50   | 10               | 33 |

Figure 39 presents a diagram of the travel time and average speed distribution. The diagram is bimodal displaying the morning and evening “rush hour” periods arising from peak congestion on highway 1. Furthermore, the travel time estimation bounds are quite large (+/- ~50% time) for a majority of the day.

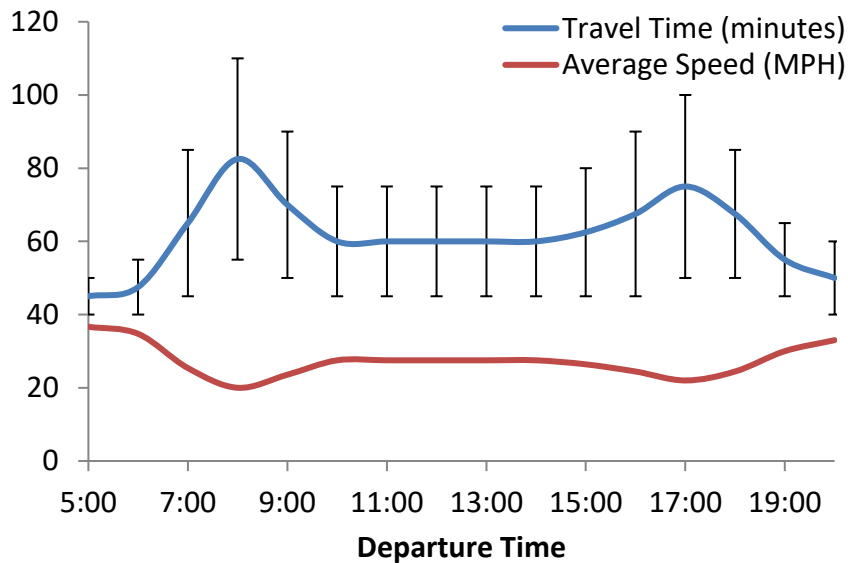


Figure 39. Malibu to Century City reference mission travel time and average speed distribution.

Finally, Figure 40 displays the inverse laborshed developed for Malibu utilizing the U.S. Census Bureau LODES data. Darker blue regions on the map represent census tracts where more workers from within the orange selection area travel to work to each day. As can be seen in Figure 40, the largest number of workers remain in Malibu. The census tracts adjacent to Malibu also appear to have a significant number of workers who commute to them each day. Expanding outwards, there are a variety of census tracts above the Santa Monica Mountains and within Santa Monica that have between four and 31 jobs. However, Century City stands out as a darker shaded census tract indicating it is one of the more common worker destinations for Malibu residents who travel beyond their own community. Upon investigation, it was found that 43 individuals conducted a daily commute from Malibu to Century City.

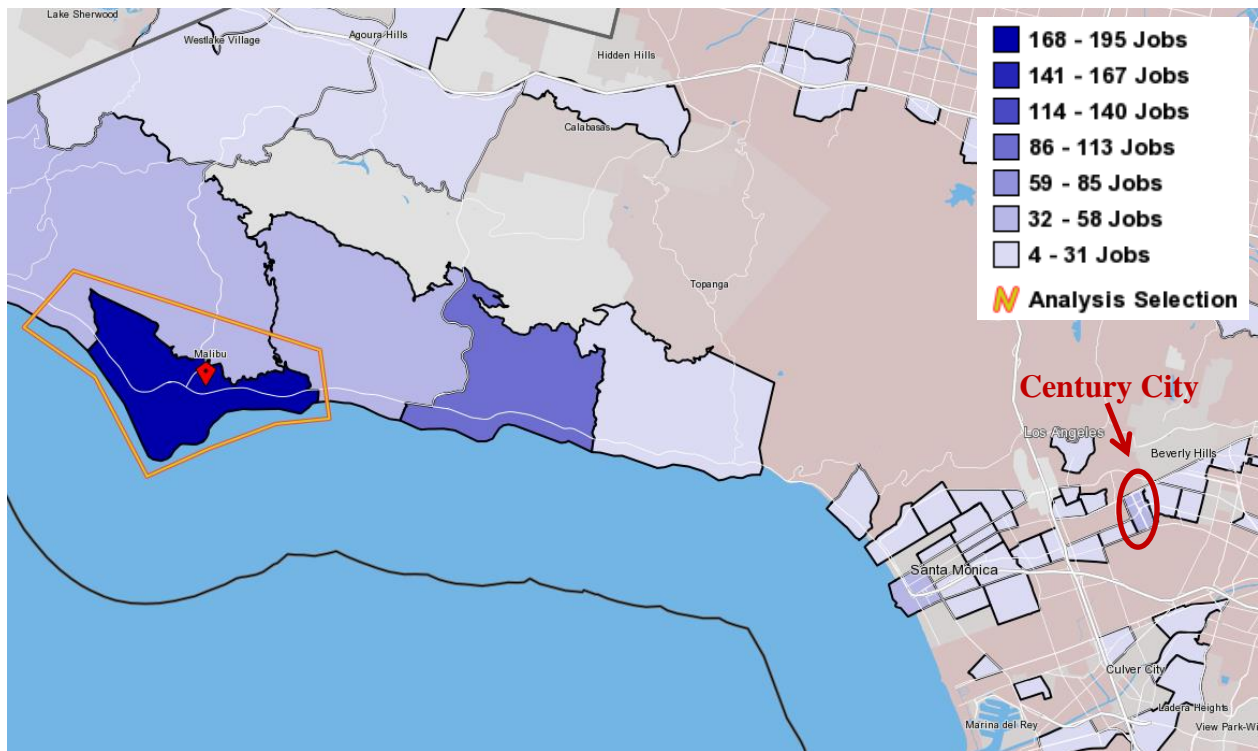


Figure 40. Malibu inverse laborshed with the Century City census tract indicated in red. *Image developed with the U.S. Census Bureau OnTheMap application. <http://onthemap.ces.census.gov/>.*

#### 4.2.2 San Bernardino to Glendale City Center Reference Mission

The San Bernardino to Glendale City Center reference mission captures a potential wealthy commuter, extreme commuting market. San Bernardino is one of the two major counties of the Inland Empire located east of Los Angeles. It is home to over 2 million people, many who commute into Los Angeles County for work. Glendale is a significant business city center north of the Los Angeles city center and roughly 55 miles west of San Bernardino. Glendale is located at the southern end of the San Fernando Valley, and as a result major ground transportation networks into the city are constrained by the surrounding mountains. Interstate 5 passes through Glendale and is a major conduit for commuters funneling from the San Fernando Valley into Los Angeles, or vice versa.

Figure 41 displays the primary route from the chosen San Bernardino origin point, a wealthy community of Rancho Cucamonga, to the Glendale City Center. The route follows highway 210 along the base of the mountains. There are a variety of alternative routes running parallel to 210 that may also provide congestion relief. Despite this significant ground transportation infrastructure, the reference mission of 44 miles requires 45 minutes during low traffic periods and may take as long as 160 minutes, a 255% congestion penalty, during peak weekday commuting periods.

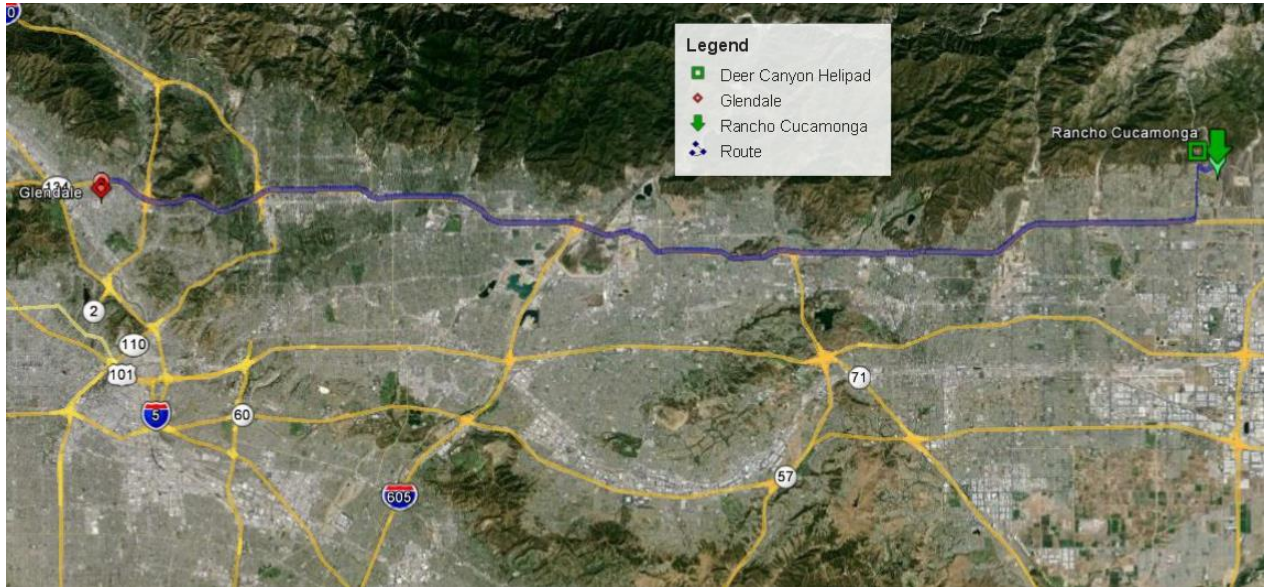


Figure 41. San Bernardino to Glendale City Center reference mission. © 2016 Google.

### 4.2.3 Antelope Valley to Los Angeles City Center Reference Mission

The Antelope Valley to Los Angeles City Center reference mission captures a mega commuting market. The Antelope Valley is located north of Los Angeles on the far side of the San Gabriel Mountains. The valley is home to over 475,000 people with Palmdale and Lancaster as its two principle cities. Although a 70 mile drive from Los Angeles, the Antelope Valley has become a low cost suburban community to the greater Los Angeles area. Numerous commuters pass over the few roads through the mountains each day to enter Los Angeles.

Figure 42 displays the primary route from the Antelope Valley origin point in Lancaster to the Los Angeles City Center. The shortest commuter route is to take the N3, a small road with a single lane in each direction, through the San Gabriel Mountains. The triple lane highway 14 passes north to the San Clarita Valley connecting to Interstate 5 and is a commonly used alternative during peak traffic times that. The reference mission is 61.5 miles by the N3 and 70.5 miles by highway 14. Without congestion the trip may be completed in 80 minutes, but during peak periods it may take as long as 130 minutes, a 60% congestion penalty.



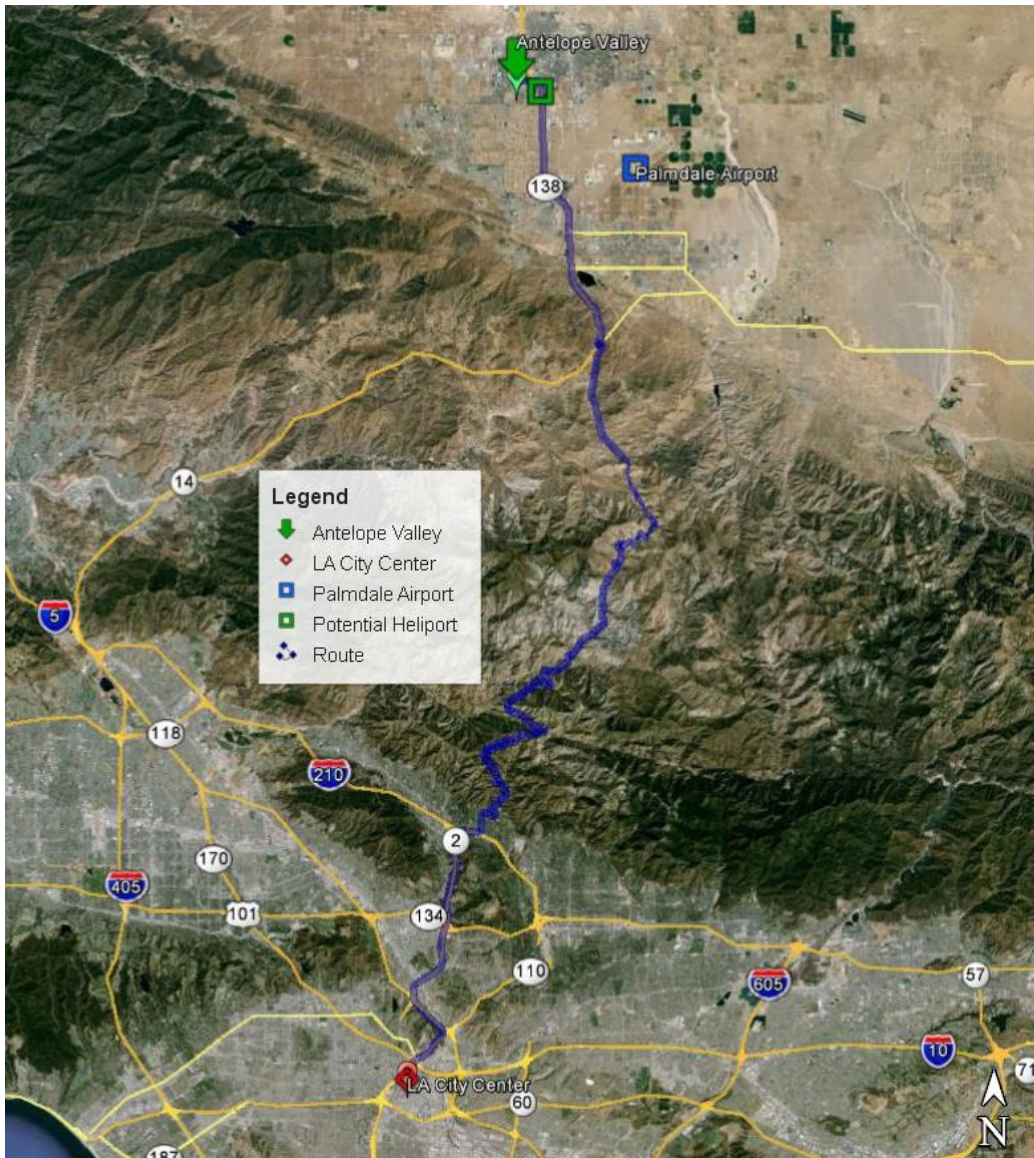


Figure 42. Antelope Valley to Los Angeles City Center reference mission.  
 © 2016 Google. Map Data: CSUMB SFML, CA OPC.

### 4.3 Non-Commute Point to Point Reference Missions

While the daily commute reference missions captured potential ODM markets for high income commuting and mega commuting communities, the non-commute point-to-point reference missions capture potential consumer demand for a diverse set of alternative ODM missions including business, recreation, and private transportation. Unlike commuter missions, point-to-point mission demand is unlikely to be temporally or directionally consistent. While commuting demand is typically concentrated in morning and evening peak periods, often in a single direction of travel, point-to-point missions may be sporadically distributed throughout the day and involve transit from any given location to a variety of other locations.

Considering the large diversity of potential point-to-point ODM aircraft missions, this case study considered a set of six reference missions that captured three distinct categories of likely early adopter markets.

The first set of point-to-point reference missions characterized travel from one city center to another city center (inter-city missions). Such services are currently provided by helicopters for large businesses that may have locations in multiple cities in Southern California, such as banks or movie production studios. These inter-city trips come in two distinct flavors. First, there is travel between two major cities in a region that are often separated by significant distance or geologic features. For example, these ODM aircraft missions may involve flight between Los Angeles and cities in Southern California including Santa Barbara, San Bernardino, or San Diego. In addition to avoiding potential ground congestion, the benefit of ODM Aviation for these missions is to cover the long distances more rapidly. To capture this potential market, a San Diego City Center to Los Angeles City Center reference mission was considered.

The second flavor of inter-city mission involves short distance transportation between the L.A. central business district (CBD) and an “edge” or “satellite” city that surrounds the CBD. Edge cities are a concept introduced by Joel Garreau in 1991 to describe the rise of new, dense urban developments with significant office and retail space on the outskirts of traditional CBDs [152]. Garreau noted the rapid, top-down development of these edge cities attracted businesses and residents through shorter commutes, less congestion, and lower property values than the crowded CBD. While most major cities in the U.S. now have  $8 \pm 2$  edge cities or secondary downtowns, Los Angeles has 45 circumferential employment sub-centers (the most of any American city) [146]. With this quality, Los Angeles was anticipated to have an especially large demand for ODM aircraft services between the CBD and its edge cities or between the edge cities themselves, especially during peak congestion periods. Employment sub-centers and edge cities in the L.A. basin include Century City, Glendale, and Long Beach, among others. To capture this potential market, a Los Angeles City Center to Long Beach reference mission was considered.

The second category of non-commute point-to-point missions considered in this case study were missions from one location within a metropolitan region to another location, or an “intra-city” mission. Unlike inter-city missions, intra-city missions as considered in this case study involve short trips between points of interest or suburban areas in or around a city, rather than from one major business district to another.

Intra-city missions are potentially quite diverse in their characteristics, therefore three reference missions were developed to simulate various possible intra-city mission of starkly different requirements. The first was from the Beverly Hills Hotel to the Los Angeles International Airport. The second was from a Redondo Beach community to Dodger Stadium for a baseball game. The third was from a Rancho Palos Verdes community to the nearby Torrance Memorial Hospital for medical services.

The final non-commute point-to-point mission considered in this case study represents a long distance trip for a recreational purpose. As displayed in Table 14, numerous helicopter charter companies currently offer flights to popular recreation and tourist locations such as Palm Springs, Big Bear, or local wineries. These missions share common traits that are distinct from the previously presented reference missions; these traits include long distance travel through

congested ground networks and geologic barriers such as mountains or bodies of water. For this case study a single recreation reference mission was defined from San Marino to Palm Springs.

For the sake of brevity, the point-to-point reference missions are only briefly introduced in this section. The full development of these missions may be found in Appendix A.

#### 4.3.1 San Diego City Center to Los Angeles City Center Reference Mission

The San Diego City Center to Los Angeles City Center reference mission captures a long distance inter-city mission. Demand for such travel exists for business, personal travel and tourism purposes. Numerous helicopter charter companies currently offer flights between these two city centers.

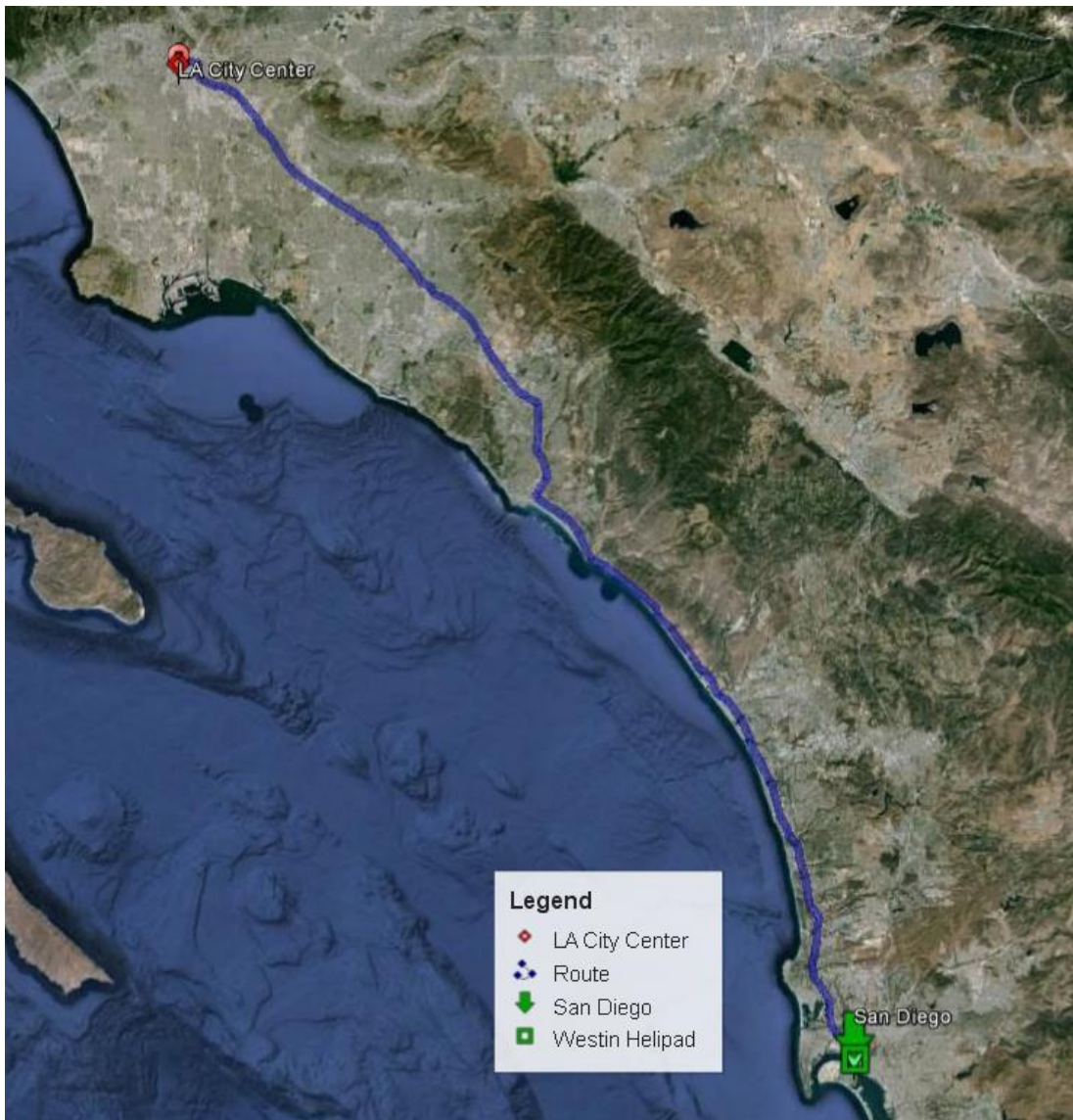


Figure 43. San Diego to Los Angeles City Center reference mission.

© 2016 Google, Map Data: SIO, NOAA, U.S. Navy, NGA, GEBCO, LDEO-Columbia, NSF, USGS.

Figure 43 displays the primary driving route from the San Diego City Center to the Los Angeles City Center. This reference mission is 122 miles and the trip may be completed in 110 minutes by car without congestion. During peak periods the same trip may take as long as 240 minutes, a 118% congestion penalty. While the demand for ODM aircraft services may be in part to avoid congestion during peak periods, it will most likely be driven by a desire to reduce the long nominal travel time between these two city centers.

#### 4.3.2 Los Angeles City Center to Long Beach Reference Mission

The Los Angeles City Center to Long Beach reference mission captures a mission from a central business district to an edge city. The origin and destination points were selected as Olvera Street and the Long Beach city beach, respectively, to characterize tourist travel between two popular cultural locations. Figure 44 displays the primary driving route from the Los Angeles city center to Long Beach. This reference mission is 26.5 miles. Without congestion the trip can be completed in 35 minutes, but during peak periods it may take as long as 100 minutes, a 185% congestion penalty. This suggests that demand for this ODM aircraft mission may primarily exist during peak travel periods, but ground transportation may be adequate during other periods.

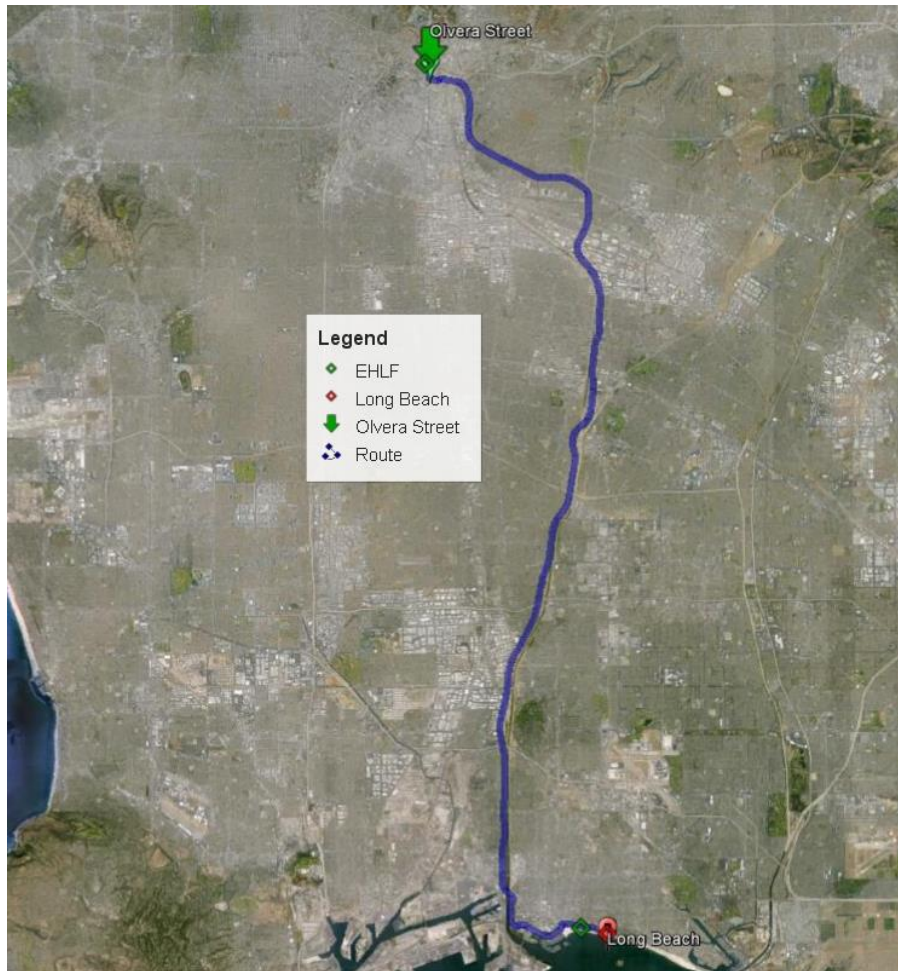


Figure 44. Los Angeles City Center to Long Beach reference mission.  
© 2016 Google, Map Data: USGS, LDEO-Columbia, NSF, NOAA.

### 4.3.3 The Beverly Hills Hotel to Los Angeles Airport Reference Mission

The Beverly Hills Hotel to Los Angeles Airport (LAX) reference mission captures a short distance mission from a suburban area to a major public transportation hub. Demand for this type of mission is heightened by strict arrival deadlines at LAX and the high cost of travel delay in the form of a missed flight. Figure 45 displays the primary driving route from the Beverly Hills Hotel to LAX. This reference mission is 13 miles and may be completed in as little as 26 minutes without roadway congestion. However, during peak congestion periods the trip may take as long as 90 minutes, a 245% congestion penalty. The ground transportation route involves significant travel on highway 405 which is recognized as one of the most congested highways in America. This suggests that demand for this ODM aircraft mission may exist throughout the day, but especially during peak travel periods in order to provide rapid and reliable transportation to LAX.

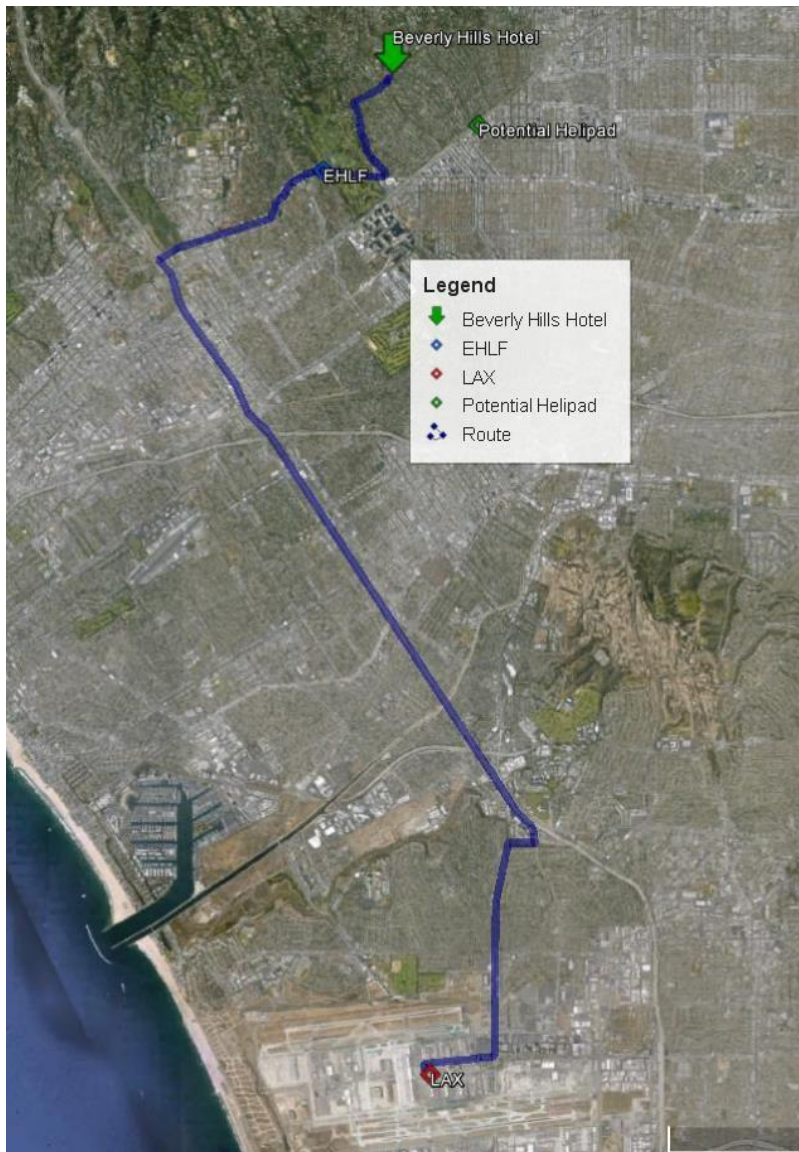


Figure 45. Beverly Hills Hotel to Los Angeles Airport reference mission.  
© 2016 Google. Map Data: USGS.

#### 4.3.4 Redondo Beach to Dodger Stadium Reference Mission

The Redondo Beach to Dodger Stadium reference mission captures a short distance mission from a suburban area to a major sporting venue. Demand for this type of mission is heightened by unavoidable, higher than average congestion as 56,000 fans converge before the first pitch. Figure 46 displays the primary driving route from the Redondo Beach origin point to the Dodgers stadium. This reference mission is 22.7 miles and may be completed in as little as 35 minutes without roadway congestion. During peak, non-game day congestion periods the trip may take as long as 130 minutes, a 270% congestion penalty. However, it should be noted that the Google Maps™ mapping service, which was used to estimate travel times for this reference mission, does not account for additional congestion due to special events in its traffic predictions. Therefore, it is likely that an additional, perhaps significant congestion penalty should be applied in addition to the standard travel times presented in this study.

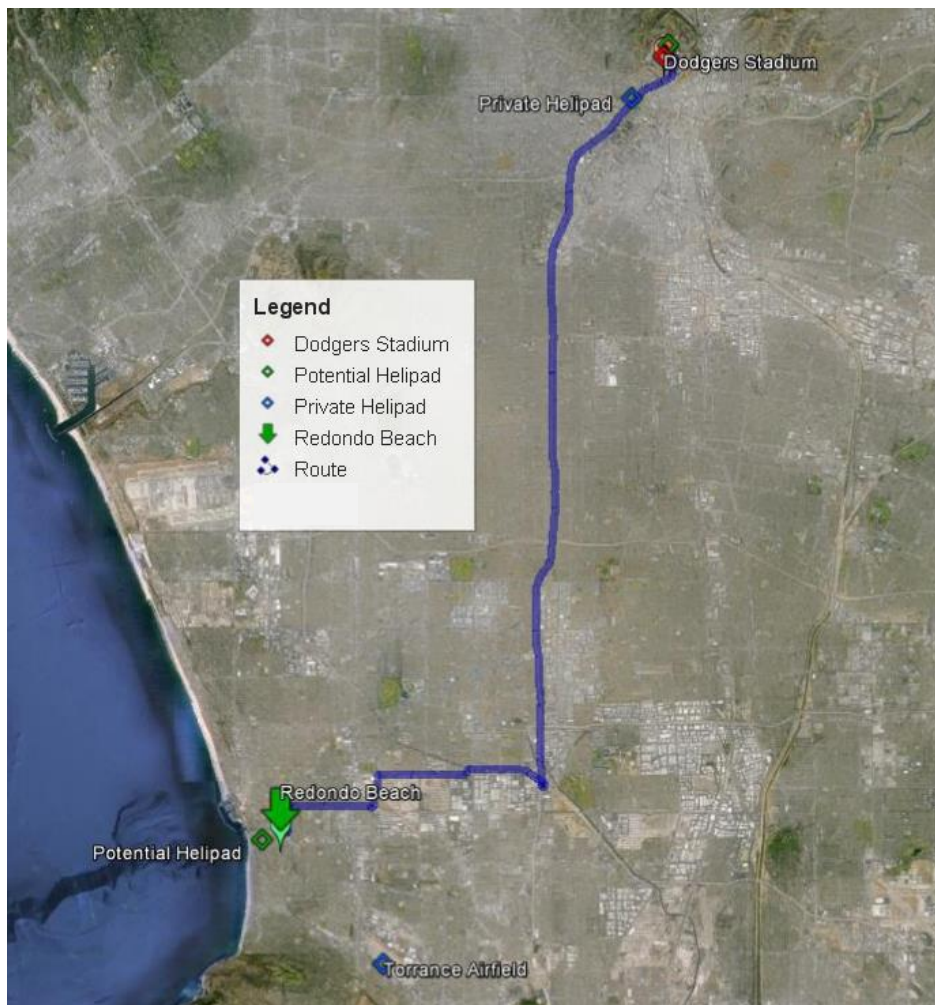


Figure 46. Redondo Beach to Dodger Stadium reference mission. © 2016 Google. Map Data: SIO, NOAA, U.S. Navy, NGA, GEBCO, USGS, LDEO-Columbia, NSF.

Taken together, the large standard travel time and additional game day congestion may create substantial demand for this ODM aircraft mission. This projection is supported by the existence of current helicopter charter services offered to the Dodgers stadium at significant price markups as

shown in Table 14. These current day services confirm that there exists a high willingness to pay for air transportation services to and from Dodgers games in the L.A. basin.

#### 4.3.5 Rancho Palos Verdes to Torrance Memorial Hospital Reference Mission

The Rancho Palos Verdes to Torrance Memorial Hospital reference mission captures a short distance mission from a wealthy suburban area to a nearby major hospital. One of the primary applications for current helicopter services is emergency medical air transportation for patients. While these services are provided at great cost and typically reserved for patients with serious conditions, ODM aircraft could potentially make aircraft-based medical transportation available to a greater number of patients.

Figure 47 displays the primary driving route from the origin point in the Rancho Palos Verdes neighborhoods to the Torrance Memorial Hospital. This reference mission is 8.5 miles and may be completed in as little as 16 minutes without roadway congestion. During peak congestion periods the trip may take as long as 28 minutes, a 75% congestion penalty. While the congestion penalty and travel time for this reference mission is lower than any of the other reference missions, significant demand for ODM aircraft medical services may still exist due to the critical nature and high value of time for such services. It should be noted, however, that medical missions are likely to occur far less often than standard commuter or other point-to-point mission types.

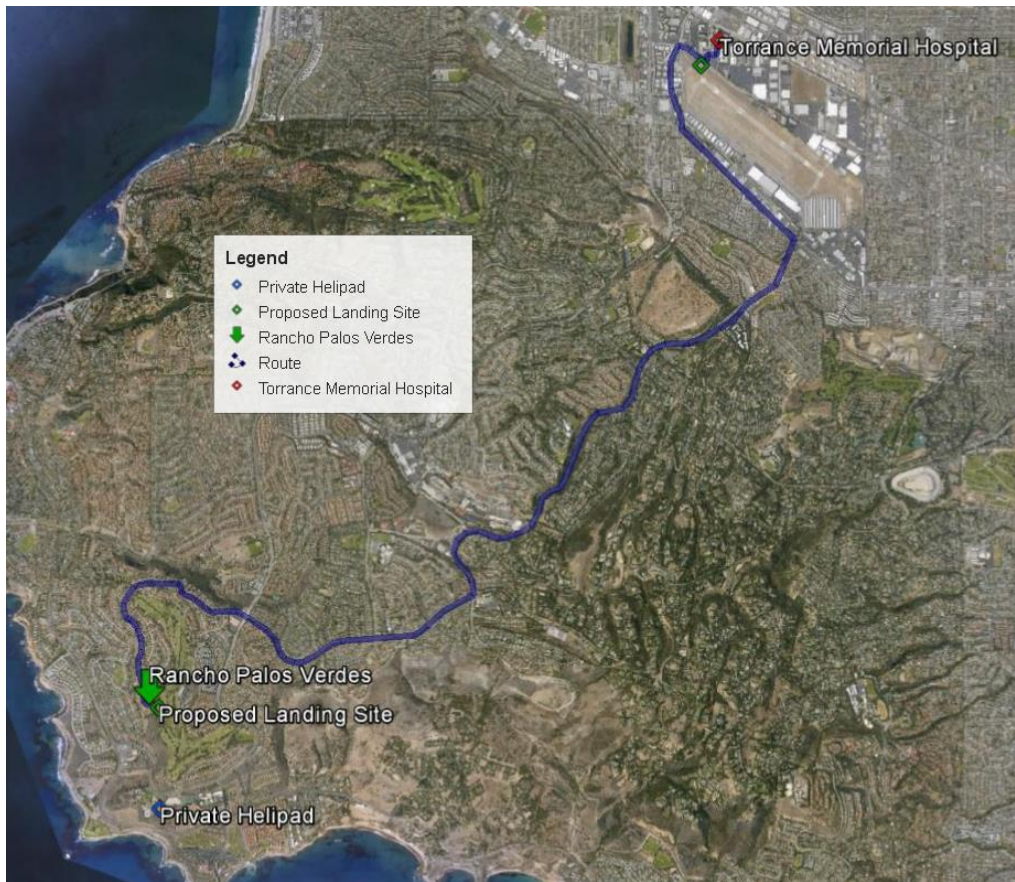


Figure 47. Rancho Palos Verdes to Torrance Memorial Hospital reference mission.  
© 2016 Google. Map Data: CSUMB SFML, CA OPS, USGS.

### 4.3.6 San Marino to Palm Springs Reference Mission

The San Marino to Palm Springs reference mission captures a long distance mission from a wealthy suburban area to a common vacation spot. Figure 48 displays the primary driving route from San Marino to Palm Springs. This reference mission is 116 miles and may be completed in 110 minutes without roadway congestion, or 140 minutes during peak congestion periods. Numerous helicopter charter companies offer flights to Palm Springs, especially for the Coachella and Stagecoach music festivals. Therefore ODM Aviation services from San Marino to Palm Springs may be considered a potential mission for the early adopter market.

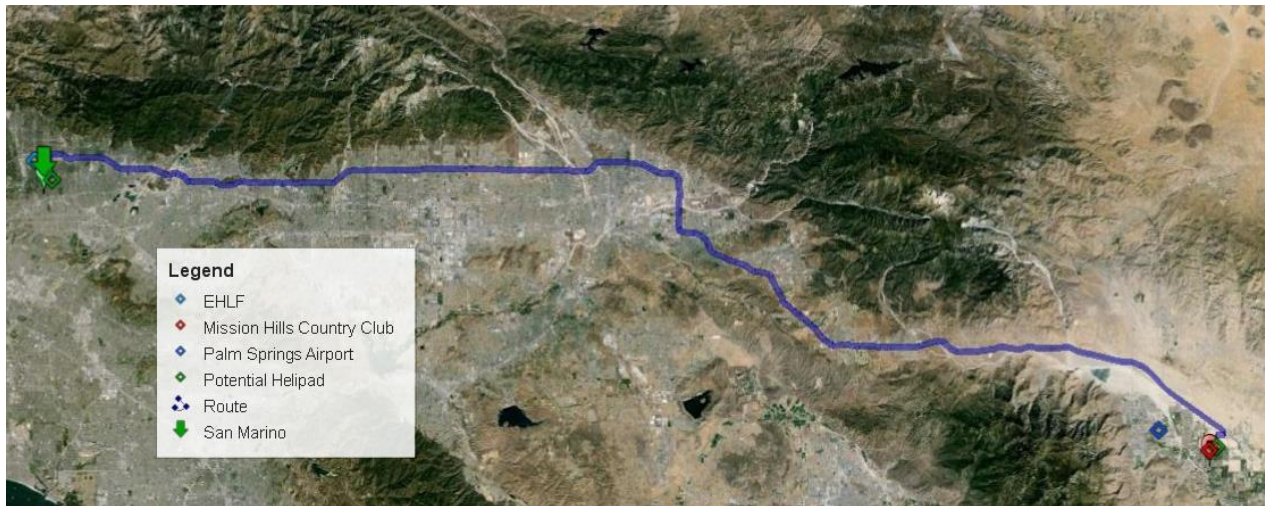


Figure 48. San Marino to Palm Springs reference mission overview.

© 2016 Google. Map Data: SIO, NOAA, U.S. Navy, NGS, GEBCO, LDEO-Columbia, NSF.

### 4.4 Randomly Selected Reference Missions

In addition to the nine reference missions selected to represent various requirements of potential early adopter markets, three additional reference missions were created with randomly selected origin and destination points. The purpose of these additional reference missions was to simulate potential ODM flights in areas other than those perceived by the author as early adopting markets. Defining the reference missions based solely upon likely early adopting markets may bias the review of ODM Aviation operational potential as the early adopter routes may share similar characteristics. Therefore, the randomly selected routes were anticipated to avoid this bias and reveal additional operational constraints, if any exist, that were not apparent in the other nine reference missions.

For the randomly selected reference missions, origin and destination points were randomly generated addresses within a defined region. The boundary of this region was rectangular with the four sides corresponding roughly to San Bernardino, Malibu, Irvine and the Antelope Valley. The addresses corresponded to positions on roadways mapped in the Google Street View program. The engine used to select these random points is publically available at Ref. [153].

This research chose to randomly select origin and destination positions on all roads within the system boundary rather than only at valid addresses. This approach was taken because it was found to provide the randomly selected reference missions with greater variability and coverage of the



geographic area. If origin and destination points were selected only from valid addresses, the missions would be clumped in densely populated regions where more homes and businesses were and therefore underrepresented less populated suburban and rural areas. While more densely populated areas may represent larger potential areas of consumer demand for ODM, it is also possible individuals further away from CBDs may have higher demand for these services. Selecting the origin and destination points equally from all roads within the reference area was therefore determined to be the more appropriate approach.

For the sake of brevity the detailed development of the three randomly selected references missions is presented in Appendix A while a summary of each reference mission is provided below.

#### 4.4.1 Randomly Selected Reference Mission 1: San Bernardino to Perris

The San Bernardino to Perris reference mission is shown in Figure 49. The origin is a suburban area in central San Bernardino, while the destination is a more rural development in the town of Perris. The reference mission is 26 miles requiring 28 minutes during low traffic periods. The trip may take as long as 70 minutes during the evening rush hour period by car. This is 150% congestion penalty. Unlike any of the nine defined reference missions, this mission is relatively short distance and occurs between two edge cities.

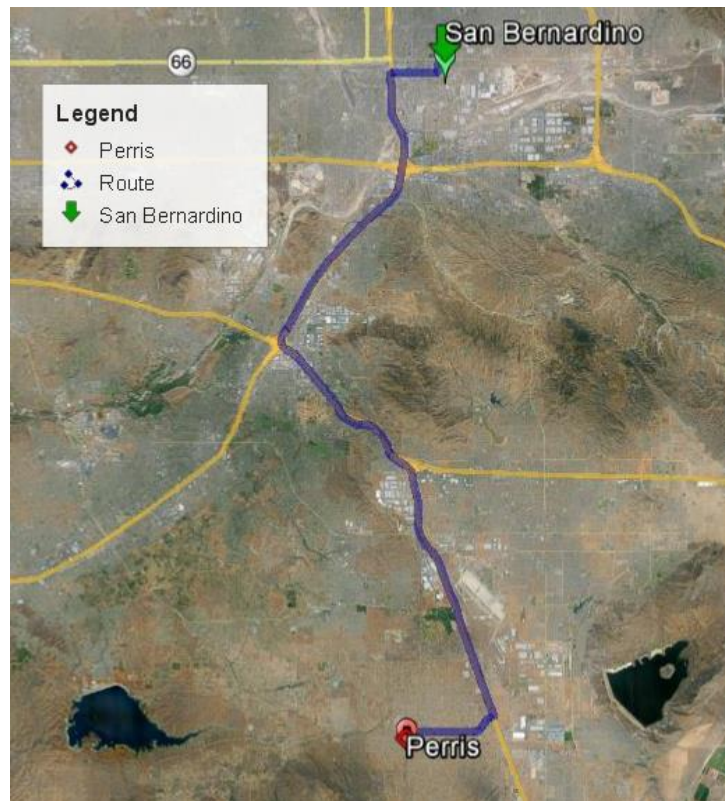


Figure 49. San Bernardino to Perris reference mission. © 2016 Google.

#### 4.4.2 Randomly Selected Reference Mission 2: Arleta to Corona

The Arleta to Corona reference mission is shown in Figure 50. The origin point is a dense suburban area of Arleta while the destination is a home on the periphery of Corona. The ground route passes out of the San Fernando Valley and crosses a large portion of the L.A. basin. The reference mission is 71 miles. It may be driven in 70 minutes during low traffic periods, but may take as long as 190 minutes, a 170% congestion penalty, during the evening rush hour period. This reference mission represents long distance transportation between two suburban areas on the outskirts of the L.A. basin.

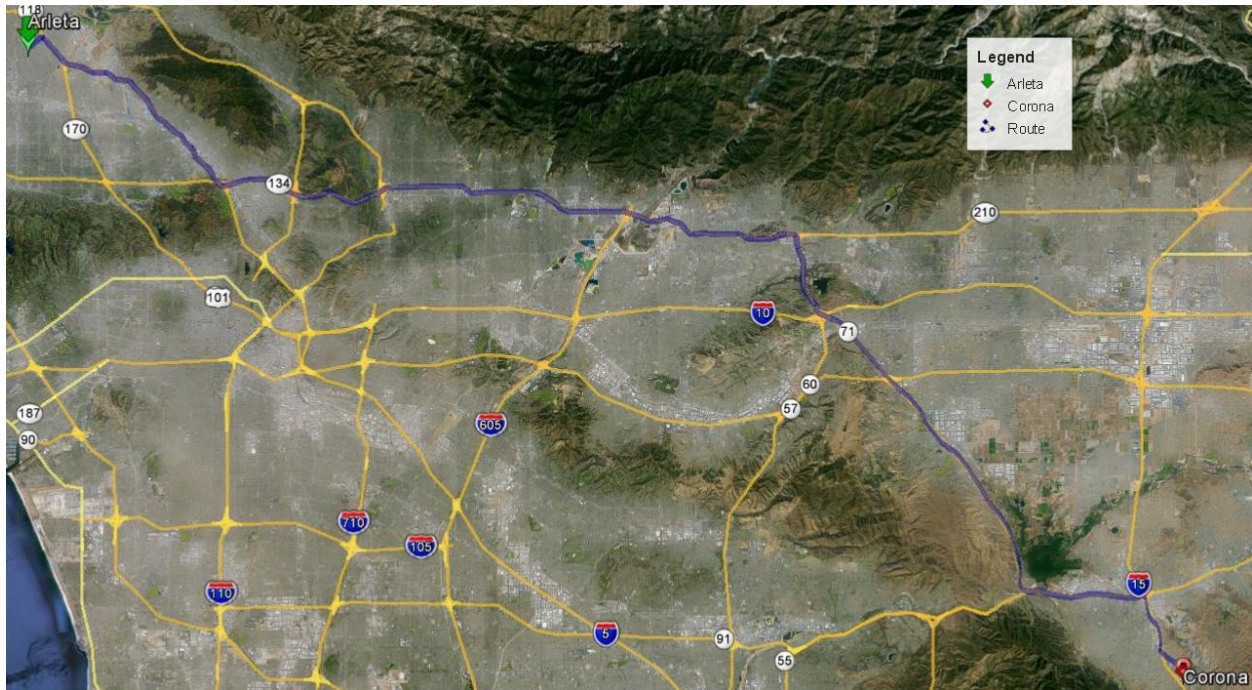


Figure 50. Arleta to Corona reference mission.  
© 2016 Google. Map Data: LDEO-Columbia, NSF, NOAA, USGS.

#### 4.4.3 Randomly Selected Reference Mission 3: Altadena to Culver City

The Altadena to Culver City reference mission is displayed in Figure 51. The origin point is a wealthy suburban area at the foot of the San Gabriel Mountains. The destination is a dense suburban area between Culver City and Inglewood. The ground route crosses the L.A. CBD and includes a portion of Interstate 405 which is a major congestion area in the L.A. basin. The reference mission is 30 miles and 40 minutes during low traffic periods, but may take as long as 130 minutes, a 225% congestion penalty, during the morning rush hour period. This reference mission represents transportation between two suburban areas near central Los Angeles.

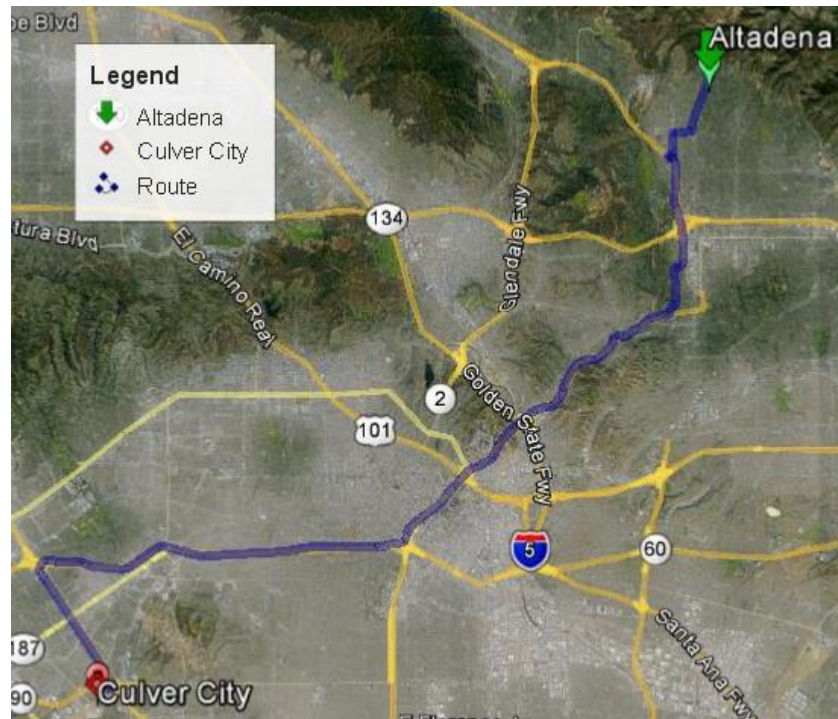


Figure 51. Altadena to Culver City reference mission.  
 © 2016 Google. Map Data: USGS, SIO, NOAA, U.S. Navy, NGA, GEBCO.

#### 4.5 L.A. Case Study Reference Mission Definition Summary

This section presented twelve reference missions to display the variety of missions proposed for ODM Aviation operations in Southern California. Nine of the reference missions were defined to specifically represent promising early adopter consumer markets; these included potential markets such as:

- wealthy commuters who may have a high willingness to pay for ODM Aviation services
- mega commuters who travel long durations and distances each day and may realize significant benefits from ODM Aviation
- businesses that desire to transport executives or employees more quickly between company locations
- tourists and event attendees who travel on highly congested routes, or may have strict arrival deadlines for concerts, sports games, or flights
- individuals who must make a planned or emergency trip to a medical facility
- vacationers who desire to travel to remote areas and avoid congestion

Section 4.2 introduced the three daily commute reference missions. The potential demand for ODM aircraft services was validated for these missions by considering conventional vehicle travel times and congestion penalties, as well as determining the number of individuals who participate in the specific commute through U.S. Census data.

From this review, the Malibu to Century City and San Bernardino to Glendale City Center reference missions were found to be promising, small volume markets. The severe congestion

penalties on these routes may create substantial demand among the affluent communities considered in the missions. However, neither of these reference missions represented a substantial market in terms of size. The total addressable market was 43 individuals for Malibu to Century City and 85 individuals for San Bernardino to Glendale. If market penetration, ride sharing of ODM aircraft and variability in demand is considered, it is unlikely these two missions would represent more than a few flights per day in the short term.

However, it should be noted that these reference missions only considered travel from a specific reference origin area to another, relatively small destination area. By considering Santa Monica as an alternative destination for the Malibu mission and the Los Angeles City Center as an alternative destination for the San Bernardino mission, the total addressable market jumps to over 800 individuals. This suggests that a larger ODM Aviation network may exist for these wealthy community daily commute reference missions if additional destinations are considered. Furthermore, the U.S. Census LODES data does not capture the commuting patterns of all individuals, so greater demand may potentially be captured than predicted in this initial analysis.

The Antelope Valley to Los Angeles City Center reference mission was shown in Section 4.2.3 to be a promising, high volume commuter market. ODM aircraft may offer significant time savings on this mega commuter route, and the total addressable market was 951 individuals. The Antelope Valley is not a highly affluent suburb of Los Angeles. Therefore, compared to Malibu or the Rancho Cucamonga community in San Bernardino, it should be expected that ODM aircraft will achieve a smaller market penetration in the 951 potential individuals of the Antelope Valley as they may have a lower willingness to pay for the service.

Section 4.3 introduced six non-commuter point-to-point reference missions. Among these missions, the San Diego to Los Angeles and San Marino to Palm Springs missions were found to represent potential high value markets. These missions both considered the use of ODM aircraft for relatively long missions (100+ miles) and therefore provide businesses and individuals with significant time savings compared to ground transportation. Since the time savings are not only significant during the peak congestion periods, these two reference missions may have stable demand throughout the whole day.

The Beverly Hills Hotel to Los Angeles Airport, L.A. to Long Beach, and Redondo Beach to Dodger Stadium missions were also found to represent potential high demand markets, however only during peak congestion times.

The Rancho Palos Verdes to Torrance Memorial Hospital reference mission was not found to provide significant potential time savings benefits for one way travel and therefore is unlikely to represent a significant early adopter market. However, ODM aircraft may offer significant time savings for medical services and may also offer new choices and capabilities to consumers. When these additional factors are considered, ODM aircraft medical services may be considered as a sizable early adopter market.

Finally, three missions with randomly selected origin and destination points were developed. These missions were not defined to simulate anticipated high value markets, and therefore would not be biased by potential similarities in the nine missions specifically defined by the researcher.

These three missions may reveal additional constraints or opportunities not present in the high value market reference missions.

Table 24 displays a summary of the twelve reference missions. The major components of the demand opportunity are listed. These include if the mission origin community was considered high income, if severe congestion (>75% congestion penalty) was experienced on the ground route, if the route was long distance (over 50 miles), and if there was an arrival deadline where being late had serious health or financial consequences. The average off-peak ground transportation time is provided, along with the maximum predicted peak ground transportation time.

Table 24. Reference missions summary.

|                                   | <b>Reference Mission</b>            | <b>Demand Opportunity</b>                            | <b>Ground Distance</b> | <b>Off-Peak Ground Time</b> | <b>Peak Ground Time</b> |
|-----------------------------------|-------------------------------------|--|------------------------|-----------------------------|-------------------------|
| <b>Daily Commute</b>              | Malibu to Century City              | High Income<br>Severe Congestion                     | 27.5 mi                | 60 min                      | 110 min                 |
|                                   | San Bernardino to Glendale          | High Income<br>Severe Congestion                     | 44.0 mi                | 60 min                      | 160 min                 |
|                                   | Antelope Valley to L.A. City Center | Long Distance  | 61.5 mi                | 80 min                      | 130 min                 |
| <b>Non-Commute Point to Point</b> | San Diego to L.A. City Center       | Long Distance  | 122 mi                 | 140 min                     | 195 min                 |
|                                   | L.A. City Center to Long Beach      | Severe Congestion                                    | 26.5 mi                | 43 min                      | 100 min                 |
|                                   | Beverly Hills Hotel to LAX          | High Income<br>Severe Congestion<br>Arrival Deadline | 13.0 mi                | 42 min                      | 90 min                  |
|                                   | Redondo Beach to Dodger Stadium     | High Income<br>Severe Congestion<br>Arrival Deadline | 22.7 mi                | 55 min                      | 130 min*                |
|                                   | Rancho Palos Verdes to Hospital     | High Income<br>Arrival Deadline                      | 8.5 mi                 | 21 min                      | 23 min                  |
|                                   | San Marino to Palm Springs          | High Income<br>Long Distance                         | 116 mi                 | 125 min                     | 185 min                 |
| <b>Random</b>                     | San Bernardino to Perris            | -  | 26 mi                  | 34 min                      | 70 min                  |
|                                   | Arleta to Corona                    | -  | 71 mi                  | 92 min                      | 190 min                 |
|                                   | Altadena to Culver City             | -  | 30 mi                  | 58 min                      | 130 min                 |

\* gameday traffic penalty not considered



## 5 ODM Aviation Operational Constraints Identification

On Demand Mobility for Aviation proposes to develop a network of small aircraft flying at low altitudes and high speeds in close proximity to many of the world’s most congested cities. However, despite the vision and effort of numerous companies and individuals over the past four decades, urban air mobility networks have not come to fruition on a large scale. The non-existence of these services provides evidence that significant barriers or constraints exist that have previously discouraged or prohibited sustainable intra-city aviation ventures.

This chapter introduces a concept of operations (ConOps) for ODM Aviation missions that provides a hypothetical mission timeline for passenger and aircraft activities. The notional ConOps was applied to each of the twelve L.A. reference missions. By evaluating the feasibility of completing the ConOps through each of the design lenses considered in the analysis approach, potential operational challenges facing the implementation of ODM Aviation were identified. Figure 52 displays the process used to identify these operational constraints and outlines the current analysis step in red.

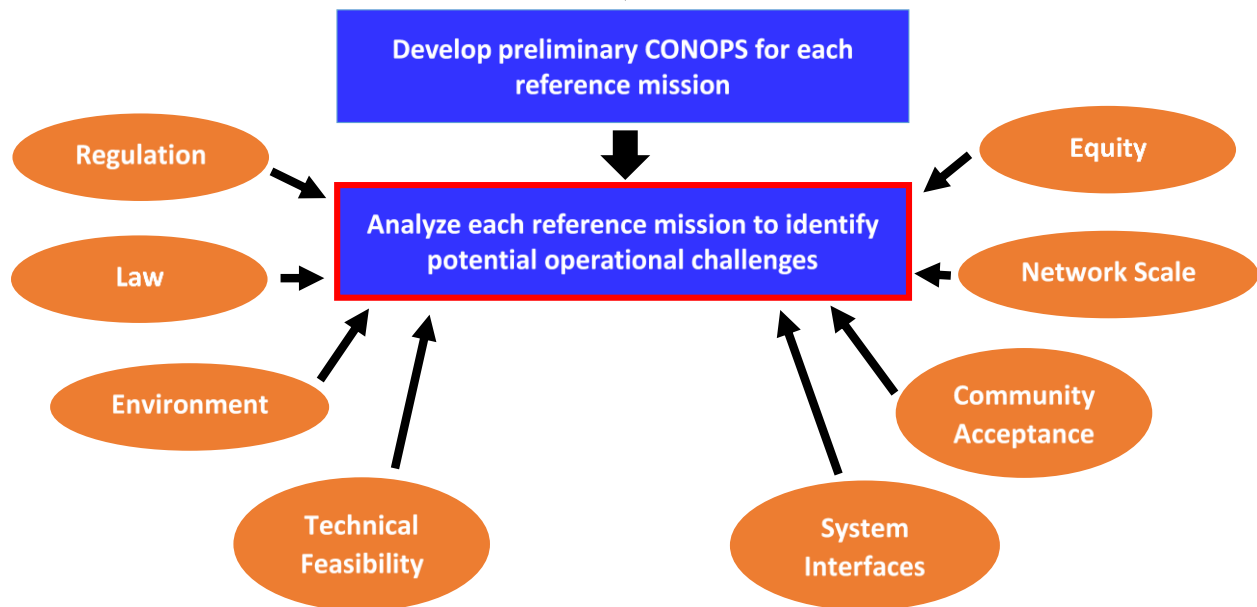


Figure 52. Reference mission ConOps evaluation process and evaluation lenses (represented in orange) used to identify operational constraints for ODM Aviation.

### 5.1 Near-Term ODM Aviation Notional ConOps Definition

In order to ascertain the feasibility and challenges of ODM Aviation network operation in the near-term, both vehicle ConOps and mission ConOps were defined to support the simulation of the reference missions. Figure 53 displays a diagram of the notional aircraft ConOps for a generic ODM Aviation mission. While any single reference mission may not require an aircraft to conduct all of the steps outlined in Figure 53, the ConOps captures all of the possible nominal operations that may be required for such a mission.

“TOLA” in Figure 53 stands for “Takeoff and Landing Area,” referring to any location an ODM aircraft may depart from or arrive at. Depending upon the V/STOL capabilities of future aircraft,

the generic term TOLA may represent a wide variety of infrastructure ranging from an airport to a heliport to an open field, or even perhaps a parking lot or empty road. Numerous terms for novel takeoff and landing infrastructure for ODM aircraft have been proposed in the literature; this thesis documented vertiport, vertipad, pocket airport, skypark, sky node and sky port. While each of these terms could potentially be used to describe ODM ground infrastructure, this thesis sought to remain as general as possible and recognize that unimproved areas such as greenspace or roadways could potentially serve as an operations area for ODM aircraft. Therefore, the term takeoff and landing area was chosen to describe any such area.

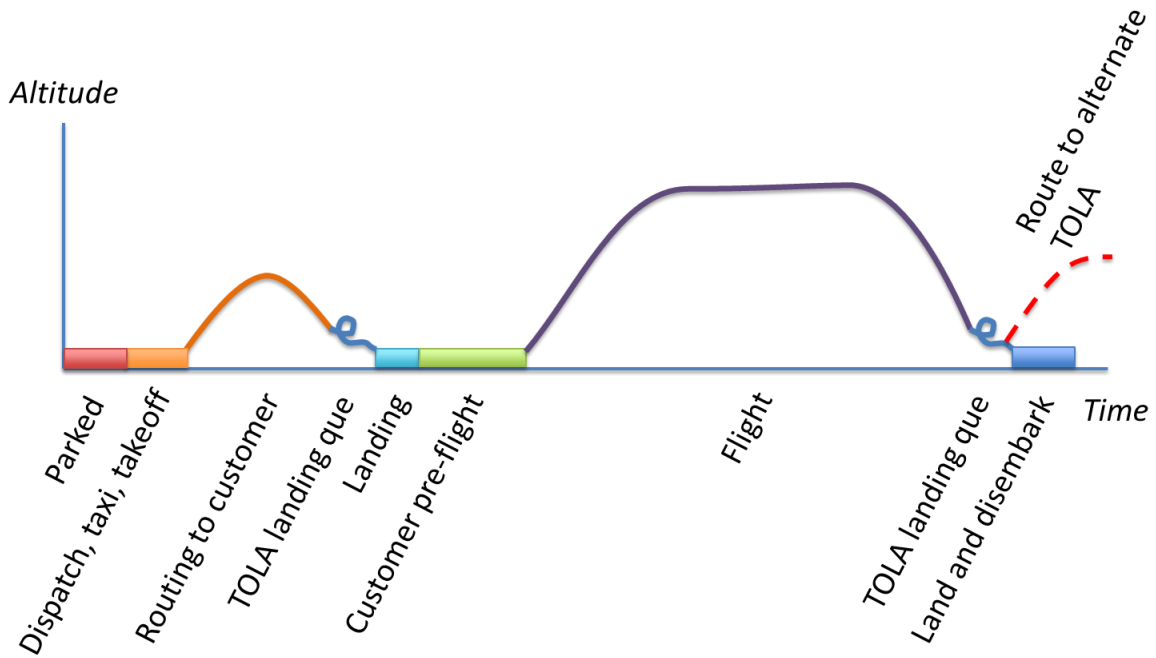


Figure 53. Notional aircraft ConOps for an ODM Aviation mission.

In addition to the aircraft ConOps, a mission ConOps was also defined to capture the necessary actions of the customers and the interfaces of the aircraft with the customers. Table 25 presents the eight step mission ConOps defined to describe the phases of a generic ODM Aviation mission. As with the aircraft ConOps, a reference mission may not require all eight of these steps, however they provide a checklist which a reference mission may be evaluated from.

Table 25. Notional mission ConOps for ODM Aviation.

| ConOps Step | Description   |
|-------------|---|
| 1           | Customer submits a travel request                         |
| 2           | Aircraft routed to nearest TOLA                           |
| 3           | Customer takes ground transportation from origin to TOLA  |
| 4           | Customer arrives at TOLA and is prepared for takeoff      |
| 5           | Flight segment  |
| 6           | Aircraft arrives at destination and customer disembarks   |
| 7           | Customer takes ground transportation to final destination |
| 8           | Aircraft recharges batteries                              |



## ***5.2 Reference Mission Operational Challenges Identification***

The aircraft and mission ConOps outlined in Figure 53 and Table 25, respectively, were applied to each of the twelve reference missions to develop hypothetical mission timelines and identify potential operational challenges that are possible in near-term conditions. Potential challenges included any situation that could influence the feasible operation of an ODM Aviation network. While some challenges were perhaps trivial in light of emerging technologies and proposed mitigation approaches, this research sought to be thorough in identifying the factors that could influence the operational potential of ODM Aviation networks.

The operational constraint evaluation for the Malibu to Century City reference mission is presented in its entirety in this section as an example. The San Diego City Center to Los Angeles City Center and the Beverly Hills Hotel to Los Angeles International Airport reference missions are included in Appendix B. While the full documentation of the ConOps review for all twelve reference missions was too voluminous to include in this thesis, Section 5.4 introduces a complete listing of the challenges identified from the review of all the reference missions.

### **5.2.1 ConOps Step 1: Customer Submits a Travel Request**

The Malibu to Century City ODM Aviation mission begins when a customer submits a travel request to the ODM service provider. Advances in telecommunications over the past decade have resulted in the proliferation of smart phones and ready access to the internet. As a result, numerous ground-based ODM service providers have developed smart phone “applications” that quickly collect the necessary geographic location information of the customer’s desired origin and destination; this data is provided to the service provider’s network logistics engine. Furthermore, more traditional, real-time booking techniques such as websites or telephone reservation systems may also support this step of the ConOps.

Considering the prevalence of mobile-based travel request and demand management systems in the ground-based ODM market, no operational challenges were perceived for ODM Aviation in the development and customer adoption of a travel request submission system.

### **5.2.2 ConOps Step 2: Aircraft Routed to the Nearest TOLA**

Once the customer travel request is received by the ODM service provider, an available TOLA near the customer must be selected as the pickup point. If an aircraft is not on-site at the pickup TOLA, then one must be routed to the location from a nearby staging area or operation. As an example of the current availability of ground infrastructure to support ODM aircraft operations, Figure 54 displays the existing TOLA infrastructure surrounding the Malibu origin point. While future ODM aircraft and operators may be certified to land and takeoff from unimproved locations (such as a greenspace or parking lot), this initial review of the ConOps restricted potential TOLAs to those that meet current-day operating regulations in order to identify the near-term challenges.

The closest TOLA to the origin point is a L.A. police helipad located 1.3 miles from the origin point. The TOLA is on the beach and has a low protective fence surrounding it. There is a public access road with available street parking. There are three other private-use heliports within ten miles of the origin. The nearest of these is the Anacapa View Estates heliport located in the mountains roughly three miles to the northwest of the origin point, and the two other heliports are located roughly seven miles to the east down route 1.



Figure 54. Current TOLA infrastructure in Malibu. © 2016 Google. Map Data: SIO, NOAA, U.S. Navy, NGA, GEBCO, USGS, CSUMB SFML, CA OPC.

While the government helipad was selected as the primary TOLA for this reference mission, the availability of the facility for ODM operations is not guaranteed as EMS or public service operations have priority operation at the facility. Furthermore, the three helipads further from the origin point are privately owned suggesting that ODM operators may have to negotiate with each owner to use these facilities. Finally, all four helipads in the Malibu area have only one touch-down and liftoff area (TLOF), and have no additional parking capacity beyond a single vehicle on the TLOF. This means that if an aircraft is conducting an operation at a TOLA or is parked on-site, then that TOLA is not available for use by any other vehicle in the network.

The lack of currently available TOLAs in the Malibu area prompted the identification of the first ODM Aviation operational challenge: *How to resolve TOLA congestion and priority use?* This operational challenge considers how priority will be assigned among operators (as well as police and EMS services), how airspace congestion in the immediate TOLA surroundings shall be managed, and who is responsible for these services. The Malibu to Century City reference mission represents a wealthy commuter community where demand is likely to be concentrated within an hour or so during the morning and evening commutes. There is only one convenient TOLA in the immediate surroundings of the origin point that has the capacity for one vehicle. Therefore it is likely there may be congestion at the TOLA as numerous ODM aircraft attempt to pick up customers during the morning commute or drop them off in the evening.

A second potential ODM Aviation challenge that arose was: *Where are ODM aircraft staged?* A key aspect of providing effective ODM services is having the network assets (vehicles) geographically distributed near areas of potential demand. While automobile ODM networks often have vacant vehicles driving on the roads in the network at all times due to the relatively low cost of operation, it is unlikely this approach will be feasible for ODM Aviation networks as the operations costs of flight are significantly higher. Therefore, ODM aircraft must be staged, or parked, in TOLAs relatively near the anticipated areas of demand.

In the case of the Malibu to Century City reference mission, the first staging option would be to stage an aircraft on the police TOLA. This approach would only allow one aircraft to be on station at a time, and it would make the TOLA unavailable for the rest of the network. Beyond reducing

the capacity of the network, it is unlikely that a vehicle would be allowed to sit on the helipad for extended periods as the facility must be available for emergency services.

A second potential vehicle staging approach would be to position multiple vehicles at the private heliports surrounding Malibu. There are four private heliports within 12 miles of the police facility. ODM aircraft could more easily be stationed at these facilities as they are not reserved for emergency operations. However, the proximity of these four helipads was not considered to fully mitigate the aircraft staging challenge as it is possible the private helipad owners may not tolerate an ODM aircraft sitting for indefinite periods of time on their property.

A third approach to vehicle staging for the Malibu to Century City mission is to stage numerous vehicles at an off-site location. Figure 55 broadens the search area around Malibu for currently available aviation ground infrastructure and reveals the nearest existing facilities with capacity for multiple vehicles are three airports located roughly 20 nautical miles (nmi) away. If new infrastructure development were considered, then a multi-vehicle staging facility could likely be developed in vacant space much closer to Malibu. Similarly, special use locations such as parking lots or fields could also be potentially used as near-term aircraft staging areas.



Figure 55. The nearest available aircraft staging infrastructure to Malibu that can currently support numerous vehicles are three local airports.

© 2016 Google. Map Data: CSUMB SFML, CA OPC, USGS.

Staging ODM aircraft this far from the potential demand center in Malibu may create delays in service to allow time to route the aircraft to the customer. Flight time from any one of these three potential staging areas would be around seven minutes in the best case scenario. This estimate did not account for the additional time that would be necessary to conduct a pre-flight check, gain departure clearance, taxi to the takeoff area (if necessary), takeoff from the staging area and then land at the pickup TOLA. Considering these factors, aircraft staging therefore represents a significant potential challenge for ODM Aviation operations in Malibu.

### **5.2.3 ConOps Step 3: Customer Takes Ground Transportation from the Origin to the TOLA**

Since many customers do not begin or end their trips directly at a viable TOLA, “first mile” and “last mile” ground transportation needs were considered. For Malibu, the nearest available TOLA was 1.3 miles from the origin point, or about a 6 minute drive during standard traffic. Customers in Malibu have a variety of ground transportation options including walking, private car, bus, taxi, or ground ODM. Resultantly, ground transportation per se was not perceived as a potential ODM operational challenge in Malibu.

However, if the customer chose to drive their own personal vehicle (as is common for commuters to a public transportation mode such as a subway network) then *private vehicle parking* was identified as a potential challenge. Many multi-modal mobility options that require first mile/last mile transportation must provide parking options at their stations to attract customers; this is the case for the Boston T and Atlanta MARTA, for example. The Malibu TOLA, while having some street parking currently utilized by beachgoers, does not have dedicated parking and likely does not have sufficient long-term parking to satisfy large-scale ODM Aviation operations.

A second potential operational challenge identified from this step of the mission ConOps was the *TOLA proximity to the customer origin point*. While the police heliport was located only 1.3 miles from the origin point, a standard rule of thumb for public transit is customers will only walk a quarter to a half mile to reach a transportation mode [138], [139]. Beyond this distance, consumers are more likely to utilize another transportation option (private car or bicycle, for example) to reach the nearest public transit station, or not use the public transit service all together.

This suggests that the current lack of geographically well-distributed infrastructure in Malibu may reduce the demand for ODM Aviation services. Customers are likely to need first mile/last mile transport. Furthermore, with few TOLAs supporting operations customers may also experience significant congestion as all ODM Aviation demand in Malibu converges on the single in-town TOLA. A TOLA congestion study for Malibu is presented in Section 5.2.9 and displays the total passenger throughput potential for the area is limited by the insufficient density of TOLAs and the turn-time of the vehicles on a TOLA.

### **5.2.4 ConOps Step 4: Customer Arrives the TOLA and is Prepared for Takeoff**

Once a customer arrives at the TOLA a variety of potential activities may be necessary in order to prepare them for the flight. These activities may include:

- Customer identity certification
- Security scan (not currently required for aircraft under 12,500 lbs)
- Customer access to the TOLA touch-down and liftoff area
- Customer and luggage loading into the aircraft
- FAA pre-flight safety review
- Aircraft startup and takeoff

Completing some or all of these tasks for the Malibu mission may require a non-trivial amount of time, especially if there is no on-site personnel and the pilot is required to exit the vehicle (presumably shutting it down) to conduct the preflight activities. On-site personnel may

dramatically speed up the preflight process, however loading the aircraft and takeoff will still require some aircraft time on the pad. As a result, a potential operational challenge for ODM Aviation is the *duration of the aircraft turn-time on the TOLA*. The aircraft turn-time is interconnected with the availability of the TOLA and influences potential ODM network congestion in the region.

While physically accessing the TOLA was not anticipated to be a challenge for the Malibu mission due to the surface level nature of the police TOLA, it was identified that *customer access to the TOLA* was a challenge for many other reference missions. Much of the existing helipad infrastructure is located on the rooftops of private buildings, inside private business compounds or in areas otherwise inaccessible to customers without an escort or access to private or secured areas.

Finally, a third potential operational constraint that is closely related to the customer access to the TOLA is the *safety and security of the TOLA*. Aircraft operations involve large machinery that frequently has exposed propellers and other hazards. Not only must customers be protected while accessing the TOLA for and operation, but bystanders must also be prevented from entering the area and being exposed to hazards. There may also be the concern of providing security from individuals who may seek to interfere with ODM Aviation operations at the TOLAs.

This last potential challenge is especially pronounced for the Malibu mission where the TOLA is a surface-level pad with a small protective fence. An individual could intentionally or inadvertently gain access to the TOLA and put themselves, the aircraft and nearby bystanders at risk of harm.

### **5.2.5 ConOps Step 5: Flight Segment**

To develop flight profiles for the flight segment of each reference mission studies were conducted concerning the airspaces, aircraft traffic and ground population densities. A variety of flight profiles were developed for each reference mission that expressed different potentially desirable features. The flight profiles were reviewed to identify potential ODM Aviation operational challenges that may arise from the flight segment step of the ConOps.

#### *5.2.5.1 Malibu to Century City Airspace Considerations*

Potential routes from Malibu to Century City may interact with numerous controlled airspaces. Flight near, under or through the various classifications of controlled, uncontrolled and special purpose airspaces may place requirements on ODM operators including various ATC clearances, equipment or procedures as summarized in Figure 56 and presented in detail in Appendix C. This research therefore sought to identify the airspaces ODM Aviation operations are likely to interact with and assess requirements or challenges they may pose.

Figure 57 displays the controlled airspaces in proximity to the Malibu origin and Century City destination points; potential ODM flight paths may interact with one or more of these airspaces. In particular, the origin point of the mission is below the floor of the LAX Class B airspace. Maximum flight velocity is therefore limited to 200 kts. Furthermore, the destination point is located within the Santa Monica Class D airspace which requires communication with ATC to enter. Table 26 presents a summary of the key characteristics of each airspace in proximity to this reference mission. It should be noted that while Class E and G airspaces are not pictured in Figure

57, ODM aircraft would almost certainly operate within both of these classes of airspaces to complete this mission.

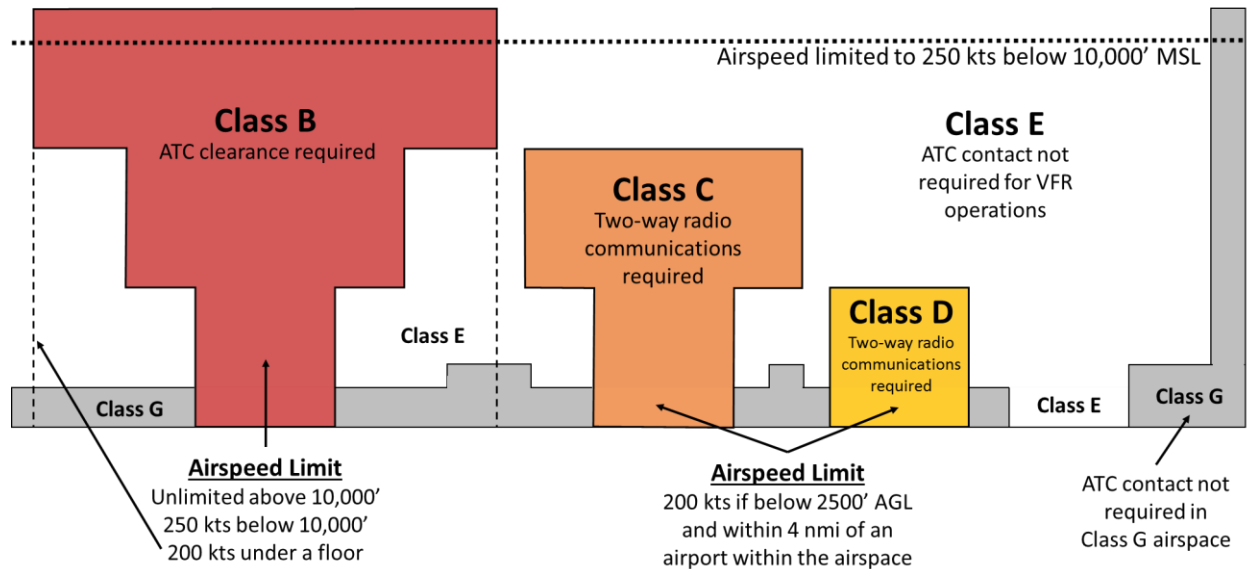


Figure 56. ATC entrance requirements and airspeed limits for aircraft operations in various airspaces for flight below 10,000 ft MSL.

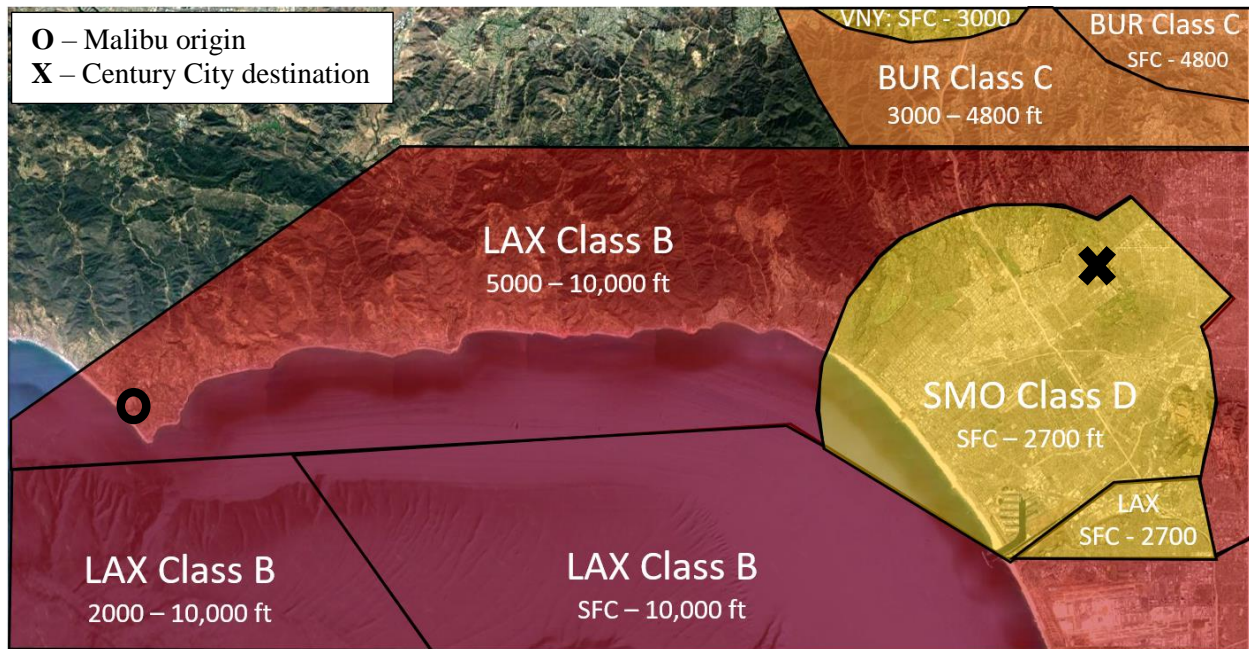


Figure 57. Class B, C and D airspaces in proximity to the Malibu to Century City reference mission origin and destination points. Airspace altitude boundaries indicated in feet above MSL.  
 © 2016 Google. Map Data: SIO, NOAA, U.S. Navy, NGA, GEBCO, USGS

Table 26. Key characteristics of airspaces near the Malibu to Century City reference mission.

| <b>Airspace</b>                  | <b>Airspace Class</b> | <b>ATC Entry Requirements</b> | <b>Airspeed Limitations</b>                       | <b>Active Hours</b>    |
|----------------------------------|-----------------------|-------------------------------|---|------------------------|
| <b>Los Angeles Intl. Airport</b> | B                     | ATC clearance                 | 250 kts inside<br>200 kts below a floor           | Always                 |
| <b>Bob Hope Airport</b>          | C                     | Two-way radio communications  | 200 kts if within 4 nmi of airport below 2500 AGL | Always                 |
| <b>Santa Monica Airport</b>      | D                     | Two-way radio communications  | 200 kts   | 7:00am –<br>9:00pm PST |
| <b>Van Nuys Airport</b>          | D                     | Two-way radio communications  | 200 kts if within 4 nmi of airport below 2500 AGL | Always                 |
| <b>Class E</b>                   | E                     | None                          | 250 kts below 10,000 ft                           | Always                 |
| <b>Class G</b>                   | G                     | None                          | 250 kts below 10,000 ft                           | Always                 |

Finally, the entire Malibu to Century City reference mission is contained within the Los Angeles Mode C Veil which sweeps out a 30 nmi radius circle from LAX. All vehicles operating in this airspace must be equipped with a functioning Mode C transponder. By 2020, all vehicles operating in this veil must also be equipped with ADS-B.

#### 5.2.5.2 Air Traffic Interaction

This section reviews potential interactions ODM aircraft may have with other aircraft through the flight phase of the mission.

*Helicopter Operations:* There are three established helicopter routes within the region of flight from Malibu to Century City. The first runs along the coastline from Malibu to the edge of the Santa Monica airspace. The second lies to the north of Malibu and follows Ventura Freeway parallel to the coast on the other side of the Santa Monica Mountains. The third route intersects Ventura Freeway route running north to south over top Interstate 405 and terminates in downtown Santa Monica. The path from Malibu to Century City also passes over three private helipads in the Santa Monica Mountains, and dozens of private, public service and emergency use helipads in Santa Monica and Century City.

*Fixed-Wing Aircraft:* The route from Malibu to Century City is crossed by numerous victor airways, three VFR transition routes and the approach and departure paths for two airports. These factors present numerous potential interactions for ODM aircraft with fixed-wing vehicles.

*Unmanned Aircraft Systems:* UAS represent an emerging challenge for the safe operation of aircraft. The FAA recorded 1200 incidents of UAS close calls with aircraft in 2015, and a majority of these incidents occurred in controlled airspaces near airports where UAS are not permitted to fly without ATC approval. Considering that ODM aircraft will operate at low altitudes in areas removed from airports and surface-level controlled airspaces, the likelihood of interaction between UAS and ODM aircraft is even more pronounced than for current commercial, fixed-wing operations.

While a great deal of experience has not yet been gained with the interaction of aircraft, helicopters and UAS in low altitude airspaces, it was assumed that such interactions will be more likely for ODM aircraft operations that occur below 400 ft over densely populated areas outside of surface-level ATC airspaces. With these assumptions, the Malibu to Century City reference mission is most likely to experience interaction with UAS air traffic near the origin point in Malibu and the destination point in Santa Monica. Flight over water, the Santa Monica Mountains, or at higher altitudes may lessen the likelihood of interaction with UAS.

Figure 58 displays a section of the Los Angeles Terminal Area Chart that depicts the flight area for this reference mission. Moving from west to east (Malibu to Century City) it may be seen that five victor airways converge just east of the origin at fix point SADDE. Large aircraft may be using these routes to approach or depart either Los Angeles international Airport or Santa Monica Airport.

Approaching Century City, five more federal airways span north to south. Three of these federal airways are R-NAV routes while the other two are victor airways. Van Nuys airport is oriented perpendicular to the reference mission, and arriving and departure routes will pass directly over ODM flights on a line of sight path from Malibu to Century City. Similarly, Santa Monica airport is oriented such that arriving and departing vehicles may pass over century city. Finally, three VFR transition routes are indicated by red arrows in Figure 58. General Aviation aircraft commonly transition through the LAX Class B airspace along these routes.

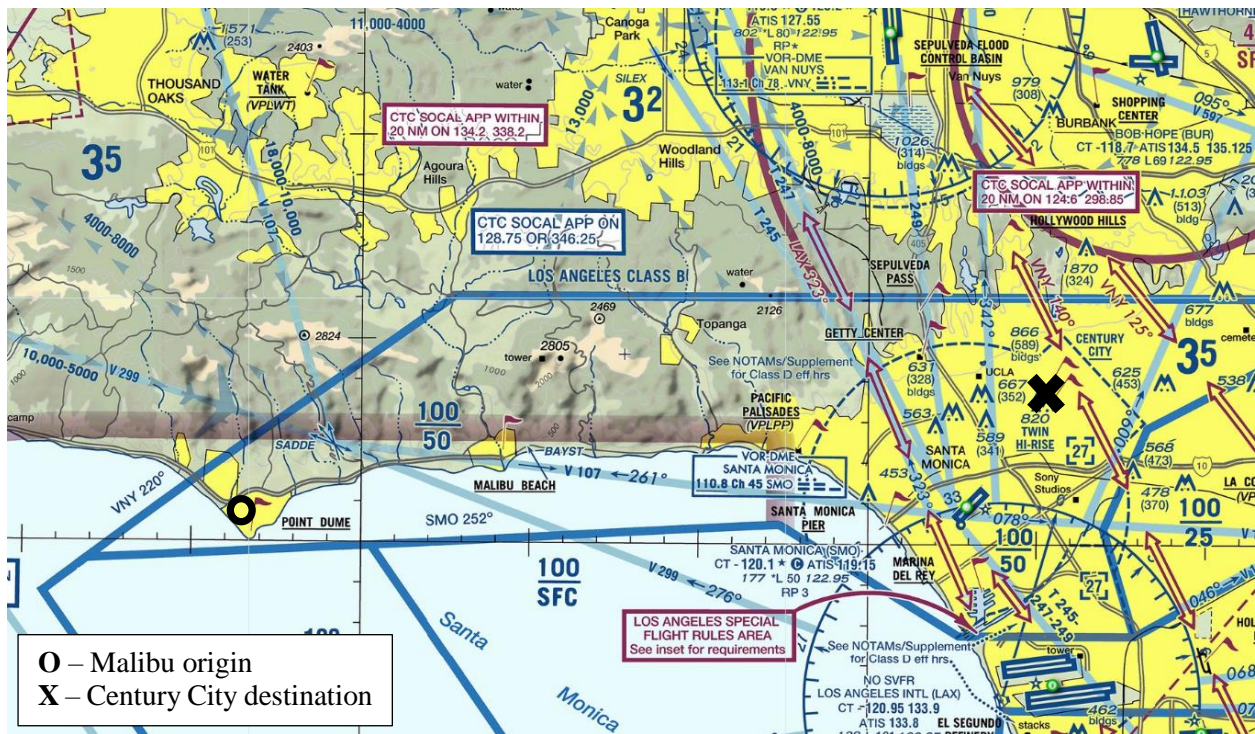


Figure 58. Los Angeles FAA terminal area chart for the Malibu to Century City reference mission.



### 5.2.5.3 Ground Population Noise Exposure

Figure 59 displays the 2012 population density of U.S. Census block groups along the reference mission. This data was used to understand population overflight characteristics of each potential flight path. ODM aircraft operations at low altitudes may expose bystanders on the ground to loud noise. Therefore, one potential desirable trait of flight profiles is to minimize ground population noise exposure by rapidly gaining altitude, or avoiding overflight of areas with high population densities.

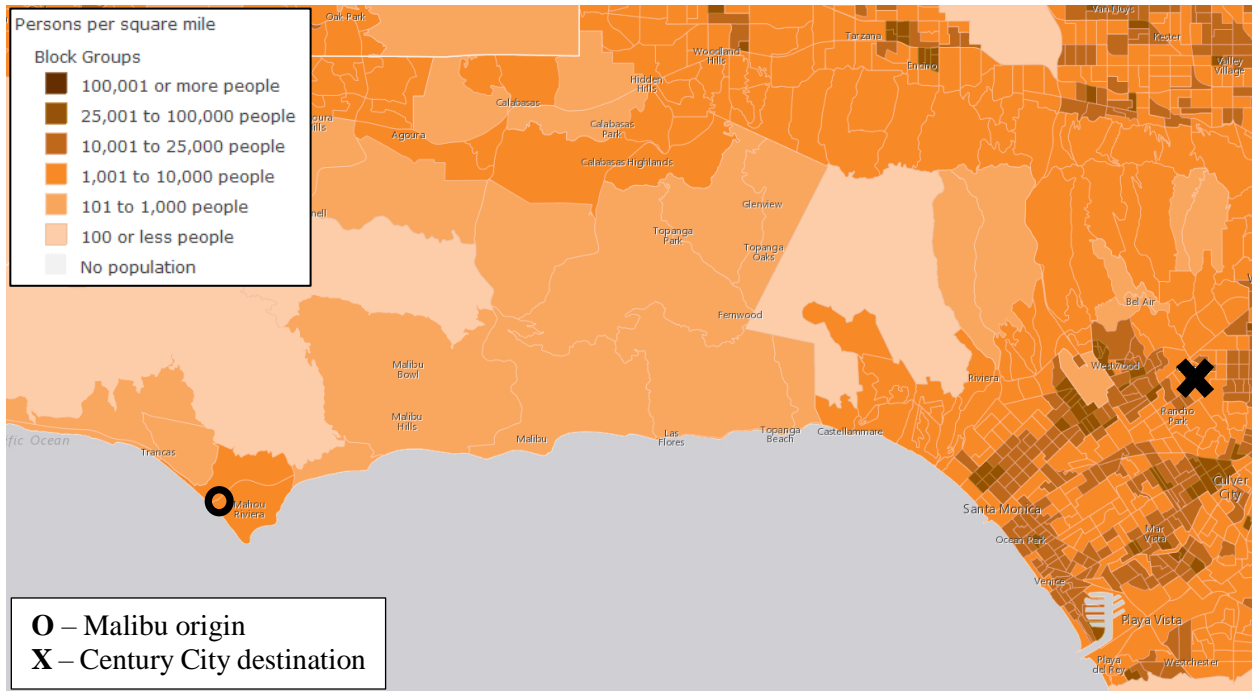


Figure 59. 2012 population density of census block groups surrounding Malibu and Century City  
*USA\_Population\_Density map © 2013 Esri, retrieved from www.arcgis.com.*

### 5.2.5.4 Mission Flight Profile Development

A variety of potential flight profiles were developed to meet the needs of the Malibu to Century City reference mission. Each flight profile provided different benefits and was subject to different constraints based upon the airspaces they accessed or the potential traffic they encountered. Figure 60 displays three potential routes for the Malibu to Century City mission overlaid on the Los Angeles Terminal Area Chart.

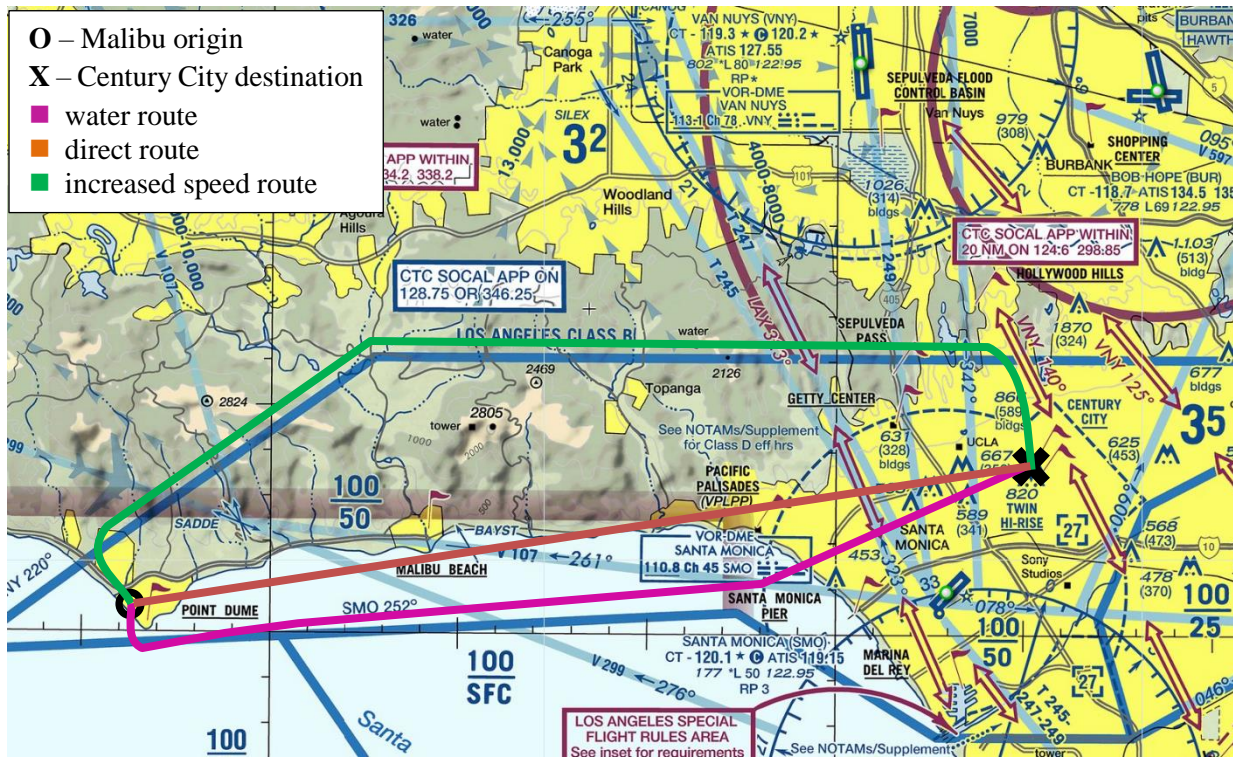


Figure 60. Malibu to Century City flight profile development.

1. Water Route: The water route sought to maximize flight time over open water in order to reduce noise exposure on the ground. The flight occurs in Class G and E airspace and requires ATC access to the Santa Monica Class D airspace during specific operating hours. The maximum speed for the entire route is 200 kts.

Flight Profile: This route departs from the Malibu helipad due south immediately taking the climb and cruise portions of the mission over water. The flight turns to an easterly heading at the boundary of the Class B airspace and climbs to a desired cruise altitude. The cruise leg of the flight occurs offshore traveling at up to a maximum allowable speed of 200 kts. The route crosses victor airway V299. Should ODM operations become highly dense, it may be necessary to travel beneath the victor airway at an altitude of less than 1200 ft to avoid interaction with large aircraft. Before entering the Santa Monica Class D airspace the pilot (or automation) must establish and maintain two-way radio contact with Santa Monica tower between 1500-0500Z; no special action is necessary at other times as the airspace reverts to Class G. If the pilot or ATC desires for the flight to avoid the Class D airspace until landing and descent, the flight may ascend to 2700 ft MSL and fly overtop the Santa Monica airspace while remaining below the LAX class B airspace. The flight proceeds over Santa Monica maintaining necessary clearance above and around obstacles. The flight is completed by landing at the on-site destination helipad in Century City.

Trip Analysis: A preliminary analysis of the flight segments and total trip duration was conducted; results are presented in Table 27. Flight speeds, altitudes and accelerations were assumed, although these may not represent the exact capabilities of future ODM aircraft and were not necessarily optimized for this route.

Table 27. Malibu to Century City water route trip analysis.

| <b>Mission Leg</b> | <b>Altitude (MSL)</b> | <b>Velocity (KIAS)</b> | <b>Distance (mi)</b> | <b>Duration (min)</b> |
|--------------------|-----------------------|------------------------|----------------------|-----------------------|
| Takeoff            | 0 to 100              | 0                      | 0.0                  | 0.17                  |
| Climb              | 100 to 2000           | 125                    | 2.0                  | 0.83                  |
| Cruise             | 2000                  | 200                    | 21.4                 | 5.58                  |
| Descent            | 2000 to 100           | 125                    | 2.0                  | 0.83                  |
| Landing            | 100 to 0              | 0                      | 0.0                  | 0.25                  |
| <b>TOTAL:</b>      |                       |                        | 25.4                 | 7.66                  |

2. Direct Route: The direct route passes over the neighborhoods of Malibu and through an extended portion of Santa Monica.

Flight Profile: This route follows a direct line of sight between the Malibu helipad and the Century City helipad. The aircraft climbs to a cruise altitude that mitigates noise concerns from individuals on the ground and provides appropriate clearance for obstacles. The vehicle may travel at a maximum speed of 200 kts. The remainder of the flight profile is similar to the water route.

Trip Analysis: Table 28 presents a preliminary analysis of the flight segments and total duration of the direct route.

Table 28. Malibu to Century City direct route trip analysis.

| <b>Mission Leg</b> | <b>Altitude (MSL)</b> | <b>Velocity (KIAS)</b> | <b>Distance (mi)</b> | <b>Duration (min)</b> |
|--------------------|-----------------------|------------------------|----------------------|-----------------------|
| Takeoff            | 0 to 100              | 0                      | 0.0                  | 0.17                  |
| Climb              | 100 to 2000           | 125                    | 2.0                  | 0.83                  |
| Cruise             | 2000                  | 200                    | 19.7                 | 5.14                  |
| Descent            | 2000 to 100           | 125                    | 2.0                  | 0.83                  |
| Landing            | 100 to 0              | 0                      | 0.0                  | 0.25                  |
| <b>TOTAL:</b>      |                       |                        | 23.7                 | 7.22                  |

3. Increased Speed Route: The increased speed route was designed to balance extra distance traveled with the higher airspeed permitted outside of overlying Class B airspace boundaries. The route avoids operations that reduce maximum airspeed from 250 kts to 200 kts including travel within four nautical miles of Class C or D primary airports, or travel under Class B airspace shelves. The route also has the potential benefit of reducing flight over densely populated areas of downtown Santa Monica or near the low altitude airways emanating from LAX. However, the aircraft must climb steeply to pass over the Santa Monica Mountains, and the route may interact with approach and departure paths for Van Nuys airport.

Flight Profile: The increased speed route departs from the Malibu helipad and proceeds northwesterly to cross out from under the overlying Class B airspace as rapidly as possible while gaining altitude over the shoreline. The vehicle then continues to climb above the

Santa Monica Mountains. After passing beyond the Class B airspace boundary, the path turns to the northeast to follow along the border of the airspace. The vehicle may accelerate up to 250 kts airspeed. The route crosses through three victor airways where care must be taken to avoid the congested altitudes above 4000 ft MSL. The path turns due east following the curvature of the overlying Class B airspace and the flight profile descends to below 3,000 ft MSL to pass under the outer layer of the Bob Hope Class C airspace. Since the flight does not enter the airspace, no speed reduction or contact with the tower is necessary. At this point the route will pass through numerous victor airways, and most significantly the approach and departure path for Van Nuys airport. When at an appropriate point to the northwest of Century City, the aircraft reduces speed to less than 200 knots and turns towards Century City passing beneath the Class B airspace shelf. The flight then proceeds into Santa Monica airspace and lands in a similar manner as the previous flight profiles.

Trip Analysis: Table 29 presents a preliminary analysis of the flight segments and total duration of the increased speed route.

Table 29. Malibu to Century City increased speed route trip analysis.

| <b>Mission Leg</b> | <b>Altitude (MSL)</b> | <b>Velocity (KIAS)</b> | <b>Distance (mi)</b> | <b>Duration (min)</b> |
|--------------------|-----------------------|------------------------|----------------------|-----------------------|
| Takeoff            | 0 to 100              | 0                      | 0.0                  | 0.17                  |
| Climb              | 100 to 3000           | 125                    | 3.1                  | 1.30                  |
| Cruise             | 3000                  | 250                    | 21.9                 | 4.57                  |
| Cruise             | 3000                  | 200                    | 0.7                  | 0.18                  |
| Descent            | 3000 to 100           | 125                    | 3.1                  | 1.30                  |
| Landing            | 100 to 0              | 0                      | 0.0                  | 0.25                  |
| <b>TOTAL:</b>      |                       |                        | 28.8                 | 7.77                  |

Table 30 provides a comparison of the total distance and duration of the three Malibu to Century City mission flight profiles. The direct route is the least distance and duration, however it runs along the coastline where a current VFR helicopter route exists. On high traffic density days this route could become crowded. Furthermore, although the coast has relatively low population, the direct route does fly over recreational beaches and homes and may therefore raise noise or viewshed concerns.

The water route is slightly longer and takes the ascent and cruise leg of the flight over open water away from the helicopter route and population. When approaching Santa Monica the route passes directly over the dense downtown population, however. Furthermore, extended flight over water may present new safety requirements and require different certifications for ODM aircraft.

Finally, the increased speed route requires ascent to a higher altitude, covers more distance and takes longer. The flight also passes over more land area with population as well as state forests and parkland. The increased speed route, as the name implies, also requires greater energy to travel at higher speeds. Therefore, the increased speed route is likely to be considered by the pilot as the last option if weather or congestion degrade the other two routes.

Table 30. Malibu to Century City flight profile comparisons.

| <b>Flight Profile</b> | <b>Distance (mi)</b> | <b>Duration (min)</b> |
|-----------------------|----------------------|-----------------------|
| Water Route           | 25.4                 | 7.66                  |
| Direct Route          | 23.7                 | 7.22                  |
| Increased Speed Route | 28.8                 | 7.77                  |

The three flight profiles presented are examples of options that a pilot may choose from for an ODM aviation mission from Malibu to Century City. While each of these flight profiles presents some advantages and disadvantages, there are numerous other flight possibilities. For example, a pilot may choose to fly a hybrid direct/water route that realizes the benefits of off-shore flight for the first half of the mission, but also travels through the relatively sparsely populated area north of Santa Monica for the latter half of the trip. A pilot may also choose to use a totally different flight profile such as ascending to 5000 ft MSL and entering the overhead Class B airspace shelf, for example. This would allow the flight to proceed without noise concerns at a maximum speed of 250 kts, but requires approval and routing from the LAX ATC.

#### 5.2.5.5 *Potential ODM Challenges from the Flight Segment*

Based upon the flight profiles developed for the Malibu to Century City reference mission, three potential challenges for ODM aviation were identified. The first challenge concerned *how ODM aircraft interact with ATC and access controlled airspaces*. Between 7:00am and 9:00pm PST all three flight profiles required ATC permission to enter the Santa Monica Class D airspace. Since Century City is located within this surface-level airspace, there is no possible flight profile that can complete the mission without ATC contact. ATC interaction was perceived as a potential challenge because as ODM Aviation networks increase in scale, low altitude ATC needs may substantially increase compared to the volume of flights handled today and the workload may exceed the current system’s capacity to support. In this situation, an ATC controller may not permit some ODM operations to enter controlled airspaces such as the Santa Monica Class D airspace. Furthermore, if ODM aircraft become autonomously flown, there are currently no standards or approaches for an autonomous pilot to request airspace access.

The second ODM Aviation challenge from the flight phase of the mission concerned *how ODM aircraft will fly safely with increased densities of vehicles in an airspace*. Currently, flight densities in most areas are relatively low. In convergence points where aircraft operations come together, either ATC is responsible for providing separation or special operating procedures and communications frequencies have been established to support self-separation. However, ODM Aviation networks may introduce hundreds to thousands of new flights in a region thereby significantly increasing flight density. Beyond interactions with other ODM aircraft, GA aircraft, and commercial aircraft, ODM Aviation will also operate at low altitudes in areas where commercial and private UAS are likely to be prevalent.

The final ODM Aviation challenge from the flight phase of the mission concerns addressing *noise annoyance to bystanders created by ODM aircraft operations*. ODM aircraft are proposed to conduct frequent operations within communities or to business locations rather than at airports. Helicopter and aircraft noise has been a significant challenge for L.A. airports and helicopter

companies attracting U.S. congressional-level action. New ODM operations are therefore likely to face significant resistance if bystander noise exposure is not addressed.

### **5.2.6 ConOps Step 6: Aircraft Arrives at Destination and Customer Disembarks**

The flight leg of the mission concludes in the Malibu to Central City reference mission when the ODM aircraft alights on the roof of the destination building. The destination has an emergency helicopter landing facility that must be converted to a commercially viable landing facility to enable the landing. Once landed, a similar set of potential ODM challenges to those identified in ConOps Steps 3 and 4 exist including *how to resolve TOLA congestion and priority, how to provide TOLA safety and security, how the customer will egress from the TOLA, and what the minimum turn-time for the aircraft is.*

In the case of this reference mission, the TOLA safety and security is less challenging due to the location of the facility on the roof of a high-rise private business. However, this feature of the TOLA increases the challenge for customer egress from the premises.

Finally, aircraft arrival revealed one additional ODM challenge: *is an alternative safe landing location available and what are the necessary reserve requirements?* If the primary destination TOLA is unavailable for a safe landing (due to congestion, another aircraft parked at the facility, or weather for example), then an ODM aircraft must divert to an alternative landing location. There are numerous nearby options for the Malibu to Century City reference mission, however it is unclear how the demand for a potential client may change if the primary destination TOLA is not available and additional ground transportation is required. Furthermore, there are not currently standards that describe the necessary reserve requirements for electric aircraft.

### **5.2.7 ConOps Step 7: Customer Takes Ground Transportation to Final Destination**

In the case of the Malibu to Century City reference mission, the final destination had an on-site TOLA and no additional “last mile” ground transportation was necessary. However, in general the proximity of an available TOLA to the final destination will be a constraint for ODM Aviation operations for the same reasons as TOLA proximity to the origin point.

### **5.2.8 ConOps Step 8: Aircraft Recharges Batteries**

ODM aviation is proposed to be enabled by quieter, more efficient electric propulsion technologies. However, due to the low specific energy density of batteries compared to chemical fuels, aircraft charging must occur more frequently and presents a new challenge for network operations. Section 2.3.1 displayed that with current battery technologies and advanced vehicles the maximum range of full-electric aircraft (that are not more than double the takeoff weight of conventional aircraft) may be as much as 175 miles. This thesis assumed a 20% range penalty to account for the hovering, takeoff, climb and landing segments of the short range Malibu mission to determine that a full-electric ODM aircraft could fly roughly 140 miles between recharge. This enabled roughly two round trip missions, or about an hour of operation, between Malibu and Century City before charging would be necessary. Although not perceived as a challenge for hybrid-electric or conventionally powered ODM aircraft, *aircraft charging* was identified as a potential challenge for ODM Aviation relying upon full-electric aircraft.

The time necessary for electric aircraft charging is subject to great uncertainty with current technologies. If aircraft are equipped with swappable batteries, charging could take only a few minutes. However, if the batteries cannot be swapped then charging could take much longer. Considering electric cars as a proxy, the state of the art Tesla Model S has roughly a 300 mile range and can fully recharge from a standard wall outlet in about 5.5 hours, or from a special “super charging” station in a little over an hour [154]. Removing aircraft from the network for an hour of recharge per roughly every hour of flight would significantly increase the number of aircraft necessary to provide reliable ODM aviation services.

### **5.2.9 Network Impacts of Mission ConOps**

Beyond the ConOps for a single mission, some of the greatest challenges ODM Aviation faces became apparent when the operations of the whole ODM network was considered. This section introduces two of these challenges with relation to the Malibu to Century City mission.

The Malibu to Century City reference mission represents a “daily commuter” mission. This means that while point-to-point demand to and from Malibu may exist at all times of the day, there is likely to be a peak period of demand in the morning corresponding to the commute to work schedule. A peak period of demand may place strain on an ODM aviation network as it requires numerous aircraft be available in the same geographic location at roughly the same time.

In addition to high TOLA congestion during peak demand periods, commuter travel is also likely to be directional where all individuals are moving from Malibu to Century City, and not vice-versa. These two attributes of the daily commuter demand patterns present *geographic balancing of ODM network assets* as another challenge for ODM Aviation. The aircraft in the ODM network may become imbalanced with demand as aircraft complete missions in Century City and do not have customers returning to Malibu. To balance the network these vehicles must take non-revenue, or “deadhead” flights to return to the customers in Malibu. Deadhead flights increase operational costs raising fares and reducing the market size.

A second network challenge for ODM Aviation is the *route capacity*, which was identified to be dependent upon the available ground infrastructure, aircraft turn-time during loading (embarkation) and unloading (disembarkation), vehicle load factor and vehicle capacity. Table 31 displays the time estimation for each mission leg and the total duration of the Malibu to Century City mission. This estimation assumed the ground transportation and aircraft assets were available and initially positioned onsite to instantly meet a customer request. Therefore this estimation was considered a lower-bound time estimate as in actual operation the ground transportation assets (automobiles) would require time to travel to the origin to pick up the client, and the ODM aircraft would likely have to transit to the Malibu helipad causing further delays.

The average one-way mission duration for an ODM aircraft from Malibu to Century City was assumed to be 15.5 minutes (embarkation, flight and disembarkation) as shown in Table 31. The return trip was assumed to carry no passengers and therefore estimated to require 7.5 minutes. Under these assumptions, the round trip time for a single ODM aircraft carrying passengers from Malibu to Century City was roughly 23 minutes. The morning rush hour was shown in Figure 39 to last from roughly 7:00am until 9:00am. Therefore, in two hours a single ODM aircraft could complete five round trip missions from Malibu to Century City if no battery recharge time was necessary and the aircraft did not return to Malibu on the final trip.

Table 31. Malibu to Century City reference mission ConOps duration breakdown.

| Mission Segment  | Distance (mi) | Time (min)    | % of Avg. Total Time |
|------------------|---------------|---------------|----------------------|
| Ground Transport | 1.3           | 6             | 27.9%                |
| Embarkation      | 0             | 5*            | 23.3%                |
| Flight           | 23.7 – 28.8   | 7.22 – 7.77   | 34.9%                |
| Disembarkation   | 0             | 3             | 14.0%                |
| Ground Transport | 0             | 0             | 0%                   |
| <b>Total:</b>    | 25 – 30.1     | 21.22 – 21.77 | -                    |

\*Impact of the variability of the aircraft turn-time assumption displayed in Figure 62.

Neglecting aircraft passenger capacity and load factor, the maximum capacity of the Malibu to Century City route is therefore dependent upon the availability of ground infrastructure in Malibu and the turn-time of the aircraft. The analysis in Table 31 assumed that each aircraft had a turn-time of five minutes on the ground during embarkation and three minutes on the ground during disembarkation. Furthermore, it was assumed that an additional 60 seconds was required for transition to allow for the departing aircraft to lift off and clear the airspace in proximity to the TOLA and for the next to enter the airspace and prepare for landing.

With these turn-time assumptions, a single aircraft mission therefore occupies the Malibu police helipad for roughly six minutes. This implies that the maximum possible throughput for the helipad (and therefore the reference mission) is roughly ten flights per hour.

Figure 61 displays a notional network ConOps for the reference mission during the first forty-five minutes of the two hour peak period. The utilization of the two helipads (one in Malibu and the other in Century City) is shown under the assumption that there was sufficient demand to operate the Malibu facility at maximum capacity for the whole period. For this analysis it was assumed the flight leg of the mission was an even eight minutes. While one aircraft was assumed to be pre-positioned at the Malibu helipad, the other three aircraft considered were assumed to be staged at Santa Monica Airport which is roughly a seven minute flight from the Malibu TOLA.

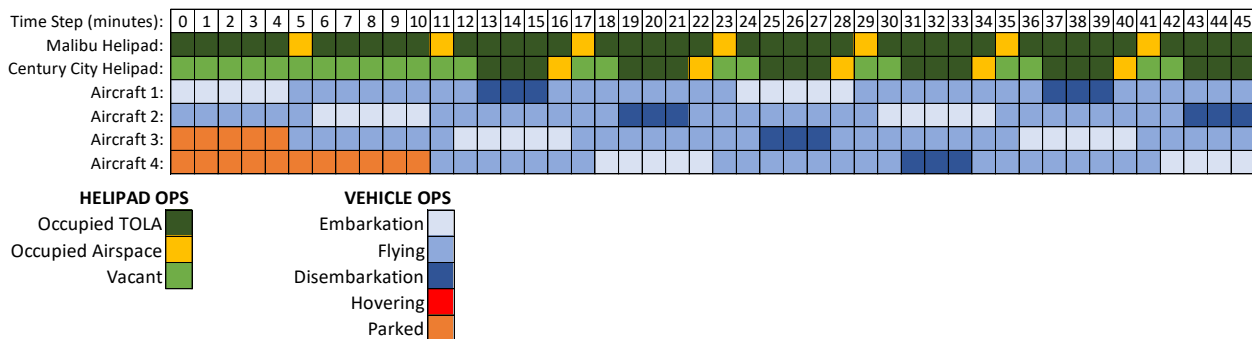


Figure 61. ODM Aviation ConOps diagram for the Malibu to Century City network assuming maximum route capacity and no aircraft charging.

With these assumptions, the ODM aviation network could achieve a maximum capacity of approximately 20 flights to Century City in the two hour peak period utilizing four aircraft. If aircraft charging were considered, then eight aircraft would be required to achieve this maximum



throughput. The total passenger throughput during this period depends upon the load factor and capacity of the aircraft. A potential benefit of peak congestion periods is that customers could be “pooled” to share a single vehicle thereby splitting costs and increasing load factor. To increase route capacity further, additional ground infrastructure must be developed in Malibu.

The maximum aircraft throughput for a single-pad TOLA (such as a helipad) directly depends upon the aircraft turn-time. For this preliminary analysis, a relatively conservative total turn-time of five minutes was assumed for takeoff operations to facilitate the activities outlined in Section 5.2.4. However, with support from ground personnel or automation that conducts these customer activities before the aircraft arrives, the turn-time may be significantly reduced. During operations in the 1970’s, New York Airways allocated three minutes for the turnaround of a 30 passenger Sikorsky S-61 helicopter [24]. Furthermore, helicopter tour operators have displayed turn-times as little as one minute.

Considering the wide variability in potential ODM aircraft turn-time that may depend upon factors such as weather conditions, ground staff and passenger capabilities, the aircraft throughput for a single-pad TOLA was studied as a function of turn-time. Figure 62 displays the aircraft throughput capacity for a single-pad TOLA for turn-times of 30 seconds up to 10 minutes. An additional 60 seconds was added to each turn-time to account for the transition of the vehicles and time for rotor vortex dissipation. Figure 62 indicates that large network throughput gains may be possible by reducing the turn-time of aircraft on the TOLAs. This is especially pronounced if turn-time is reduced below two minutes.

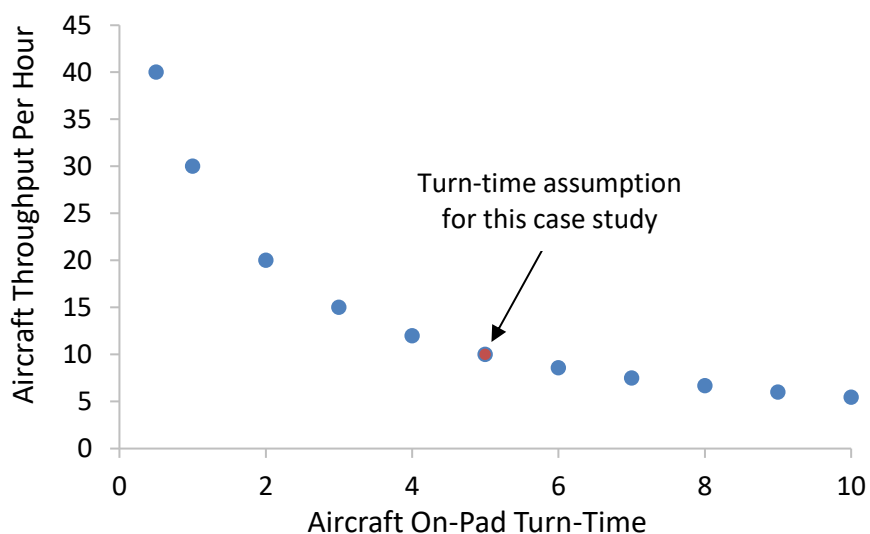


Figure 62. Dependence of single-pad TOLA throughput on aircraft turn-time.

### 5.3 Potential Operational Challenges Resulting from Negative Externalities

The ConOps review in the previous section identified a set of potential challenges that directly influence aircraft operations or customer access to ODM Aviation services. However, the implementation of urban air transportation services may also have a variety of unintended consequences on city structure and ground transportation networks that may indirectly influence the far-term ODM business concept. These unintended consequences, or negative externalities,

may be considered as additional operational challenges. Two examples of potential negative externalities are presented below.

### **5.3.1 ODM Aviation Enabled Socio-Economic Segregation**

Members of similar socio-economic classes frequently aggregate into well-defined, geographically bounded communities. This geographic segregation is a primary contributor to social-inequity as separate communities inherently have varying access to transportation, services and other necessary features. Figure 63 displays the geographic racial distribution in the L.A. basin as developed from the 2010 census by researchers at the University of Virginia. Comparing the racial distribution with the estimated household valuation map in Figure 27 revealed that White and Asians communities tend to be located in high income areas on the peripheries of the L.A. basin. Hispanic and Black communities are located in the central areas of basin or far removed commuter cities such as Palmdale and San Bernardino.

ODM Aviation may further intensify the socio-economic segregation of wealthy communities. Wealthy individuals may choose to move even further from the CBD by developing exurb communities in rural areas well beyond the current borders of the metropolitan region. These communities, known as “airparks” or “fly-in communities,” may only be accessible through aviation and therefore be nearly completely isolated from socio-economic classes that cannot afford such services.

Furthermore, the outward movement of wealthy communities could also be detrimental for city governments as their tax revenues may be diminished. The change in the tax base could in turn reduce government services and quality of life for those that remain in the city giving further reason for residents with means to move away. This negative, self-reinforcing feedback cycle has commonly been referred to as the “hollowing out” of the urban core and may lead to urban decay which is detrimental to city structure and prosperity. When the exiting population is primarily Caucasian individuals, the term “white flight” is commonly used and emphasizes the negative socio-economic segregation implications of the change in settlement patterns and city structure [143].

Finally, in addition to equity concerns, socio-economic segregation may also result in environmental challenges. 2013 research from Berkeley found that suburban developments have the highest household carbon footprint of any development type. Suburban developments account for ~50% of the total annual U.S. household carbon emissions, or about 10% of global GHG emissions [155]. This suggests that if ODM Aviation supports further urban sprawl through the outward movement of wealthy communities, it could increase total emissions by enabling a larger percentage of individuals to live in higher-emission suburban settlements.

In response to these concerns and lessons learned from transient populations in fly-in communities for resource extraction [156], local governments may place operational limits or taxes specifically on ODM operations to sustain funds and disincentive community relocation. Socio-economic segregation therefore represents a negative externality of ODM aircraft operations that may be considered a risk to the far-term scale up of ODM Aviation networks.

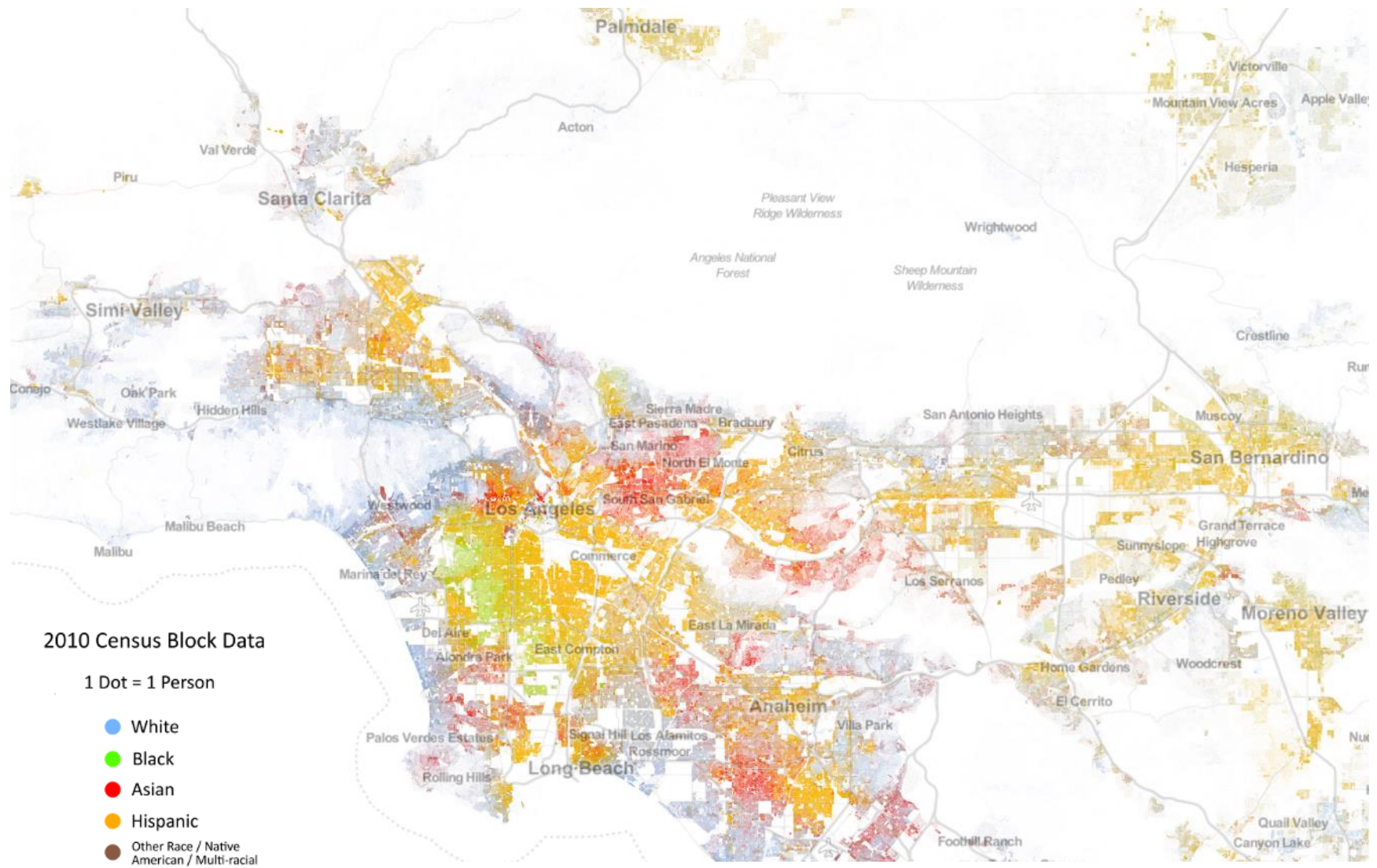


Figure 63. Geographic distribution of race in the L.A. basin. *Image copyright, 2013, Weldon Cooper Center for Public Service, Rector and Visitors of the University of Virginia (Dustin A. Cable, creator). Retrieved 12/10/2016.*

### **5.3.2 Displaced Ridership and Funding for Surface Transportation Modes**

ODM Aviation may facilitate the movement of wealthy communities to new exurbs beyond the reach of current surface transportation systems. Even if communities do not physically move to these new areas, wealthy individuals living at the terminus of public transportation lines or far out on feeder highways may prefer to use ODM Aviation to reduce the duration and difficulty of their commute. Either outcome would result in a reduction of public transit ridership and fare income, or a reduction in toll income from roadways.

The result of high-income consumers re-moding to ODM Aviation could be diminished funding for public transportation modes and roadway maintenance. A negative feedback loop could possibly be triggered where the loss of paying users reduces the quality of the experience and increases costs for those who continue to use the transportation option, thereby causing further customers to shift to ODM Aviation. Although this impact would likely be insignificant at near-term scales of ODM Aviation, the removal of income from profitable commuter rail lines that are used to subsidize inner-city subway lines may trigger social equity concerns. This represents an additional negative externality possible as a result of ODM Aviation implementation.

### ***5.4 Potential Challenges for ODM Aviation***

The walk-through review of the Malibu to Century City reference mission in Section 5.2 identified 15 potential operational challenges for ODM Aviation. Furthermore, a consideration of ODM Aviation network factors in Section 5.2.9 identified an additional two challenges concerning network load balancing and route capacity. Finally, the review of potential ODM Aviation induced negative externalities in Section 5.3 identified one additional challenge concerning potential government action that places financial burdens on ODM operations.

The approach presented for the Malibu to Century City reference mission was applied to the other 11 reference missions in an effort to identify additional challenges. It was hypothesized that the variability between the reference missions in terms of range, passenger demand, airspace interaction, ground infrastructure access and flight profile requirements, among other factors, may reveal additional potential challenges. It was also anticipated that some challenges would appear in a higher percentage of the reference missions, and that these should be considered more thoroughly as pervasive constraints for ODM Aviation operations.

The review of the 11 additional reference missions identified two further challenges that were not present for the Malibu to Century City mission. These included how a customer physically gains access to a TOLA (which was perceived to be especially difficult for rooftop facilities), and how physically close a TOLA was to the customer's destination. Interestingly, the randomly defined reference missions did not reveal any new challenges that were not already identified in the other nine reference missions. This indicated to the author that the diversity of missions defined from the promising markets were not necessarily biased towards operations that would be easier to implement than any other arbitrary mission.

Finally, the projected degree of severity of the identified challenges varied widely between the different reference missions depending upon their characteristics. In particular, one of the most influential factors was the type and location of the nearest available TOLAs. This factor directly or indirectly influenced 12 of the identified challenges. Secondly, it was found that nearly all the

missions experienced all three of the challenges from the flight phase of the mission; these challenges were ATC interaction, the safety of flight in proximity to other aircraft, and aircraft generated noise. Finally, all the reference missions faced the fundamental technology challenge of aircraft charging.

Taken as a whole, the 12 reference missions of the Los Angeles ODM Aviation case study revealed a total of 20 potential operational challenges. These challenges are presented as questions in Table 32 and associated with the mission ConOps step from which they were derived.

Table 32. Potential ODM Aviation operational challenges.

| <b>Mission ConOps Step</b> |   | <b>Potential Operational Challenge</b>   |
|----------------------------|---|--|
| 1                          | Customer submits a travel request                       | None   |
| 2                          | Aircraft routed to nearest TOLA                         | 1. Where are ODM aircraft staged?<br>2. How is TOLA congestion and priority handled?   |
| 3                          | Customer takes ground transport from origin to TOLA     | 3. Where are private automobiles parked?<br>4. How close is a TOLA to the customer origin location?  |
| 4                          | Customer arrives at TOLA and is prepared for takeoff    | 5. How does a customer access the TOLA?<br>6. What is the turn-time for the aircraft at the TOLA?<br>7. How is TOLA safety and security provided?  |
| 5                          | Flight segment  | 8. How do ODM aircraft interact with ATC and access controlled airspace?<br>9. How do ODM aircraft fly safely with increased densities of vehicles in the airspace?<br>10. How does ODM Aviation address noise annoyance to bystanders created by ODM operations?  |
| 6                          | Aircraft arrives at destination and customer disembarks | 11. How is TOLA congestion and priority handled?<br>12. Is an alternative safe landing location available and what are the energy reserve requirements?<br>13. How does a customer egress from the TOLA?<br>14. What is the turn-time for the aircraft at the TOLA?<br>15. How is TOLA safety and security provided? |
| 7                          | Customer takes ground transport to final destination    | 16. How close is a TOLA to the customer destination?   |
| 8                          | Aircraft recharges batteries                            | 17. What is the required time for aircraft charging?   |
| ~                          | ODM network-wide operations                             | 18. How is the geographic balancing of ODM aircraft handled to meet demand?<br>19. How is route capacity managed to meet demand?   |
| ~                          | Externality impacts                                     | 20. Will local governments restrict ODM Aviation operations or markets due to socio-economic segregation and reduced transportation revenues?  |

## 5.5 ODM Aviation Constraints and Issues

The 20 potential ODM Aviation operational challenges presented in Table 32 range dramatically in the severity of their impact on operations, how simple or complex they may be to mitigate, and the influence they may have on consumer demand. Furthermore, many of the challenges appear numerous times in similar steps of the mission ConOps (such as in steps 3, 4 and 6), or are interrelated with one another such as for route capacity, TOLA geographic distribution, and aircraft turn-time. To succinctly identify and communicate the most stringent challenges facing the implementation and operation of ODM Aviation networks in metropolitan areas, the 20 challenges were condensed into five *constraints* and three *issues*.

### 5.5.1 ODM Aviation Constraints

For the purposes of this thesis, ODM constraints were defined as operational factors that may inhibit the implementation or scale-up of ODM networks. Constraints were therefore common themes drawn from the 20 operational challenges that most severely influence potential ODM operations. Table 33 introduces the five constraints identified through the L.A. case study and notes key characteristics of each one. Chapter 7 reviews each constraint in detail and discusses potential mitigation approaches that may be pursued to address the constraints.

Table 33. ODM Aviation constraints.

| ODM Aviation Constraint |   | Key Constraint Characteristics  |
|-------------------------|---|---|
| 1                       | Availability of Takeoff and Landing Areas (TOLAs)           | <ul style="list-style-type: none"> <li>- The average distance from the origin to current aviation infrastructure in the reference missions was 3 miles</li> <li>- Some suburban regions were found not have existing aviation infrastructure within 10 miles</li> <li>- The lack of TOLAs amplifies aircraft staging, congestion and route capacity challenges</li> </ul> |
| 2                       | Scalability of ODM Networks under Air Traffic Control (ATC) | <ul style="list-style-type: none"> <li>- Over 40% of urban and suburban Los Angeles resides within a surface-level controlled airspace</li> <li>- 92% of the reference missions required entrance into a surface-level controlled airspace</li> <li>- A high density of ODM Aviation operations may overload ATC capabilities</li> </ul>                                  |
| 3                       | Aircraft Noise  | <ul style="list-style-type: none"> <li>- TOLAs are likely to be located within urban and suburban areas bringing aircraft operations in closer proximity to people than current airports</li> <li>- Airport and helicopter noise is already a contentious issue in many major cities</li> </ul>   |
| 4                       | Community access to TOLAs                                   | <ul style="list-style-type: none"> <li>- TOLAs must be easily accessible by the public and support inter-modal linkages to foster ODM demand</li> <li>- TOLAs are hazardous areas and appropriate safety and security must be provided</li> </ul>   |
| 5                       | Scalability of ODM Networks Operating Outside ATC           | <ul style="list-style-type: none"> <li>- Significantly increased flight densities may surpass the capacity for current rules of the road and self-separation approaches to ensure safety</li> </ul>   |

### 5.5.2 ODM Aviation Issues

For the purposes of this thesis, ODM constraints were defined as operational factors with significant uncertainty that may or may not become constraints. Issues, like constraints, vary in potential severity. Issues were not considered constraints primarily because not enough experience had been gained with the associated technologies to confirm if the challenge would materialize or be readily overcome. Table 34 introduces the three issues identified through the L.A. case study and notes key factors motivating each one.

Table 34. ODM Aviation issues.

| ODM Aviation Issue |  | Key Issues Characteristics   |
|--------------------|--|--|
| 1                  | Electric aircraft operating standards and certifications | <ul style="list-style-type: none"> <li>- There are no existing standards for minimum allowable takeoff energy</li> <li>- There are no existing electric aircraft airworthiness and pilot certifications</li> <li>- There are no existing standards for electric aircraft minimum energy reserve requirements</li> <li>- There are no existing standards for electric aircraft alternative safe landing location requirements</li> <li>- It is unclear whether distributed electric propulsion aircraft will require a multi-engine pilot rating</li> </ul> |
| 2                  | Weather conditions                                       | <ul style="list-style-type: none"> <li>- Cold temperatures may degrade electric aircraft battery performance</li> <li>- High winds may degrade network coverage or service</li> <li>- Reduced visibility and IFR flight may reduce network coverage or service</li> <li>- Frequent (especially unanticipated) reductions in coverage or service may degrade consumer demand</li> <li>- Precipitation, rough ride conditions, or hot/cold cabin conditions may reduce customer demand</li> </ul>  |
| 3                  | Interaction of ODM aircraft with UAS                     | <ul style="list-style-type: none"> <li>- How is priority established for vehicles desiring to operate in the same airspace?</li> <li>- How will ODM aircraft communicate with UAS?</li> <li>- How will ODM aircraft safety be assured during low altitude operations?</li> </ul>   |

### 5.6 Constraint Sensitivity to ODM Aviation Network Scale

A key concept identified in this research was that the severity of many of the operational constraints was dependent upon the number of ODM operations assumed to occur in a geographic area, or that *constraint severity depended upon the scale of the ODM network*. Some constraints, such as low altitude ATC, are completely non-binding for ODM operations that occur at low density; the existing ATC system can readily accept a few additional flights per day. However, as an ODM Aviation network scales up to thousands of operations per day, the ATC constraint may become a *binding* operational constraint and limit further growth of the network beyond the threshold flight capacity that ATC can support with current technology, procedures and staff.

The constraints concerning the availability of TOLAs, aircraft noise and flight density were also anticipated to significantly increase in severity with scale. For example, a few TOLAs in key demand areas may be sufficient to support the ODM network that is operating at low flight densities, however as the network scale increases these TOLAs may rapidly become congested thereby constraining further growth of the network and degrading the quality of service. Similarly, ODM aircraft noise may be more readily accepted if it is one-off and infrequent in a geographic area, however as the frequency of operations increases, communities may protest the noise more intensely. Finally, current right of way rules and ATC procedures are sufficient to ensure separation at existing levels of flight density, however these may not be sufficient if flight densities dramatically increase over metropolitan areas.

Some constraints, such as community access to the TOLAs, may maintain a relatively constant severity independent of the network scale. This constraint was anticipated to evolve in this manner as safety, security and convenient access to a TOLA are likely to be considered equally important by customers regardless of the number of flights and TOLAs in the network. The constraint is indicated to become moderately more severe due to the anticipation that TOLAs will be constructed in residential areas where safety and security may be a more significant challenge.

Figure 64 displays the notional severity and slopes of the five ODM Aviation constraints with respect to network density. The comparative severity and slopes of the constraints was the author’s opinion based on the findings of the case study. The key concept is that constraints that appear to be low severity today and are non-binding may become the most severe and binding constraints in the future as ODM Aviation scales up the number of operations in a region.

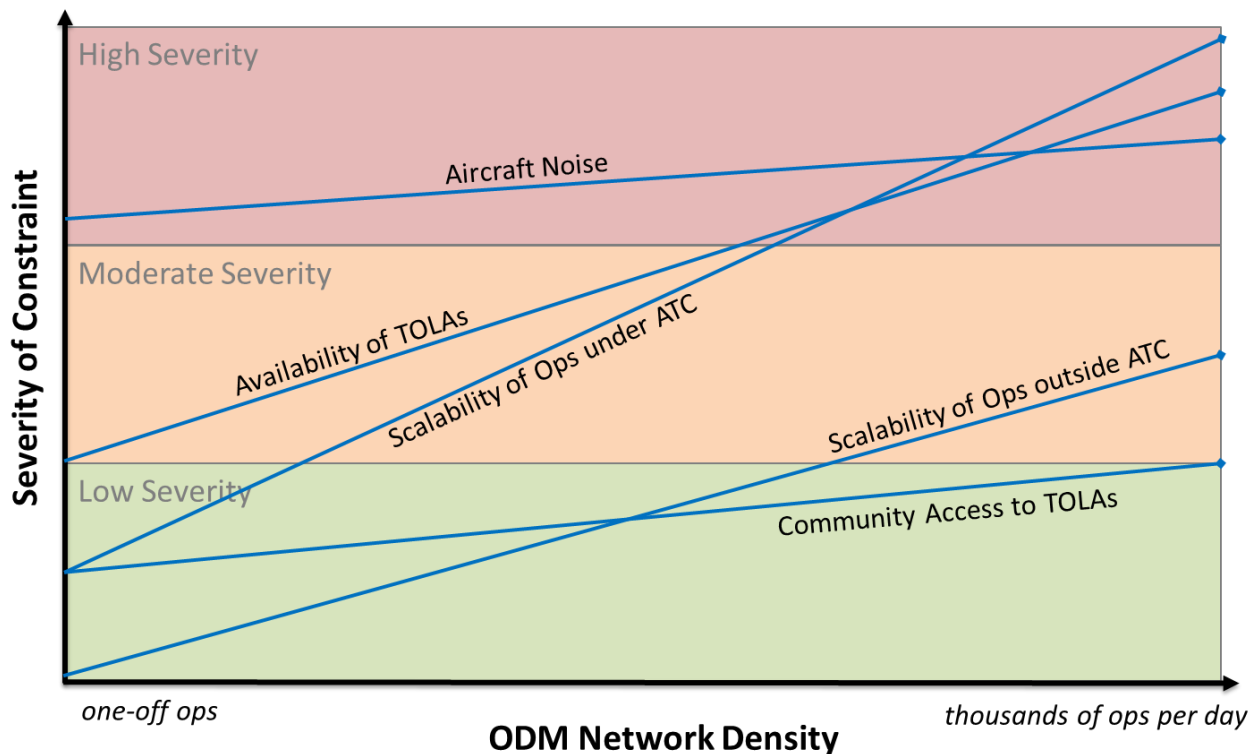


Figure 64. Notional dependency of ODM constraints on network density (scale).



## 6 Legal and Regulatory Considerations for Low Altitude Aircraft Operations

This chapter introduces the status quo of airspace design and air traffic management (ATM) in the United States focusing on regulations and their related legal interpretations. In response to nascent commercial and private UAS operations, numerous regulatory and legal questions concerning low altitude aircraft operations have recently emerged as national issues in the public eye, and in some cases have even prompted legal action [157]–[159]. This chapter summarizes these regulatory and legal questions and reviews the potential impacts they may have on future operations of UAS and ODM aircraft. Finally, a discussion is presented concerning how various aviation stakeholders may seek to address these areas of uncertainty in order to facilitate the safe, equitable use of low altitude airspace for both the flying and non-flying public.

Please note that a full review of the legal and regulatory precedents relevant to low altitude airspace operations is beyond the purview of this thesis. This thesis draws upon the preeminent case law, regulations and legal discourse available to present an impression of the status quo, identify the challenges for UAS and ODM Aviation, and proffer potential future scenarios. However, ascertaining the definitive rights of landowners and aircraft/UAS operators in low altitude airspace may only be possible by the U.S. Supreme Court or Congress.

Figure 65 displays the evaluation lenses used to identify potential challenges to ODM Aviation that may result from legal and regulatory considerations. As may be seen in the figure, not only were the relevant legal and regulatory precedents reviewed, but the dynamic nature of these institutions was acknowledged and potential evolution was considered with respect to ODM network scale and community acceptance (or conflict) of these operations. Both UAS and ODM Aviation operations were considered in this chapter due to the entwined nature of their operations and use of the same low altitude airspaces.

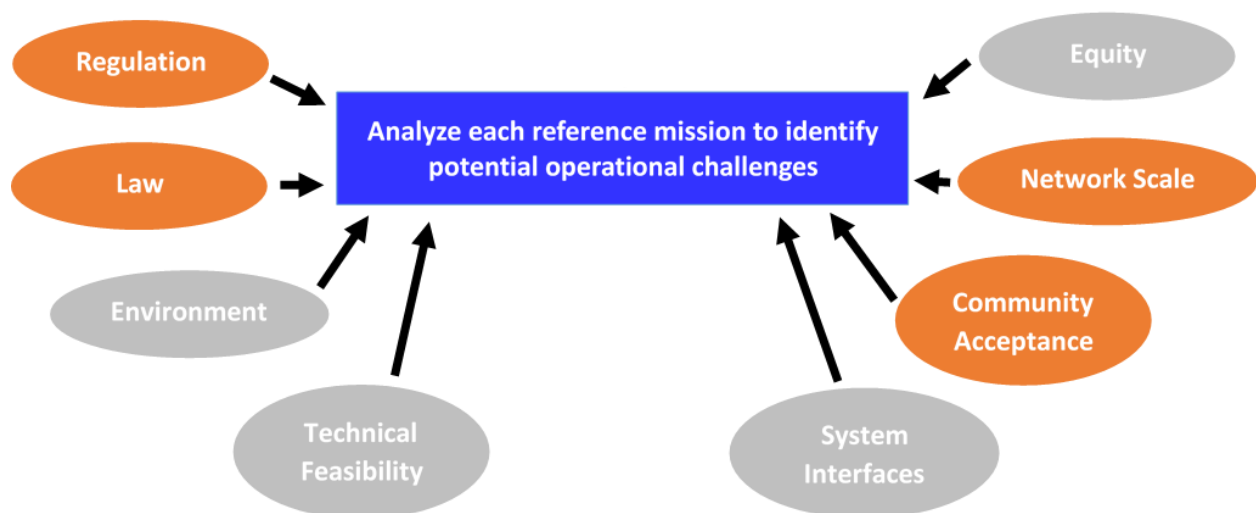


Figure 65. The evaluation lenses highlighted in orange were used to identify potential challenges to ODM Aviation that may result from legal and regulatory considerations.

## 6.1 Introduction

Over the past century the aviation industry implemented and refined a complex set of national airspace structures and air traffic management systems through national statutes, regulations, best practices, legal rulings and lessons learned from aviation incidents and accidents. These efforts have resulted in a national airspace and air traffic management system that provides efficient air transportation at unparalleled levels of safety. Furthermore, this status quo system of aviation has been widely accepted throughout the United States and is considered a crucial pillar of the modern economy.

The adoption of UAS and ODM Aviation by various communities around the U.S. will bring aviation operations in closer proximity to the public, at higher frequency and in different geographic areas than currently experienced. UAS and potential ODM aircraft are *disruptive* technologies that are not only changing the market structure of aviation, but may also alter the general public’s acceptance of overhead flight. As UAS and ODM Aviation operations become more common, numerous areas of uncertainty concerning low altitude flight, regulation and airspace ownership will surface in the status quo system as significant and potentially contentious legal and regulatory questions. While these areas of uncertainty may represent serious risks for low altitude aviation operations if they are resolved unfavorably, they have also provided the flexibility through which early market entrants have operated. If these areas of uncertainty are resolved so as to balance the needs of aircraft operators with the rights of non-aviators, then these opportunities may be preserved and protected for these new industries.

The author identified two key legal and regulatory questions that may have substantial impact upon low altitude aviation operations depending upon how they are resolved. The essence of these questions and the threats they represent for low altitude aviation are summarized in Table 35 and Table 36.

Table 35. Summary of the first legal and regulatory question relevant to low altitude aviation.

| <b>Question 1: Who has ownership and regulative authority of low altitude airspace?</b> |   |
|---|---|
| <i>Status Quo</i>   | Airspace that is typically navigated by manned aircraft today is accepted as under the sovereignty of the U.S. Government and regulated by the FAA.   |
| <i>Uncertainty Area 1</i>   | Airspace ownership and regulative authority below the “navigable airspace” limits is unclear. While the FAA has asserted regulative responsibility, local municipalities (states, counties, cities, etc.) may have a legal claim for regulating flights in these airspaces. |
| <i>Potential Consequences</i>   | Local regulation may lead to inconsistencies between adjacent airspaces potentially increasing the cost and complexity of operations while reducing safety. Blanket national regulation may infringe on local values.   |
| <i>Uncertainty Area 2</i>   | The Supreme Court has established that landowners own the enveloping airspace immediately above their land. However, it is unclear to what altitude such ownership may extend.  |

|                               |  |
|-------------------------------|--|
| <i>Potential Consequences</i> | The demarcation altitude between private and public airspace is critically important because landowners may exclude aviation operations from airspace they own through trespass tort action or seek financial compensation through government takings claims (eminent domain). |
|-------------------------------|--|

Table 36. Summary of the second legal and regulatory question relevant to low altitude aviation.

| <b>Question 2: How are landowners' rights balanced with a citizen's right to flight and use of the national airspace?</b> |   |
|---|---|
| <i>Status Quo</i>   | High altitude flight by aircraft is universally accepted by landowners. However, landowners in the vicinity of airports often maintain arriving and departing flights degrade their quality of life. While legal action against such flights has rarely succeeded in court, airports such as Santa Monica and Boston Logan have experienced increased pressure from local and national government to address such concerns. |
| <i>Uncertainty Area 1</i>   | UAS, ODM aircraft and helicopters operating in high density, at low altitudes, well away from airports are likely to raise more severe public concern and may have weak legal protections from nuisance tort action or government takings claims.   |
| <i>Potential Consequences</i>   | New regulations or legal precedence could limit aviation operations at low altitudes or require aviation easements be purchased by operators.   |
| <i>Uncertainty Area 2</i>   | UAS have already brought to a head the public concern of privacy protection from low altitude overflight.   |
| <i>Potential Consequences</i>   | Even if advanced technologies reduce aircraft noise, vibrations and emissions to a level that avoids landowner nuisance claims, low altitude operations may still face limitations from privacy tort actions.   |

If the aviation industry desires to seamlessly roll out routine UAS or ODM Aviation operations in low altitude airspaces in proximity to people, a joint effort must be made to preemptively address these legal and regulatory uncertainties concerning low altitude operation. If no action is taken, or action is taken too slowly, then narrowly-focused aviation and non-aviation actors may stimulate the development of irreversible constraints and restrictions to the detriment of low altitude aviation operations. Such regulatory irreversibilities are often not considered in traditional conceptual design approaches for technologies or industries. This review is intended to display how the first principles, system-level analysis presented in this thesis may leverage regulatory considerations to support stakeholders to make vehicle and operational requirements, investment decisions, and implementation plans.

## 6.2 The Status Quo of Aviation in the United States

The current state of air traffic management, airspace design and aircraft operational rights is the result of a century of trial, error and litigation. *Turbulent Skies* by T. A. Heppenheimer provides a thorough review of the development of ATM in the United States beginning with the lighted airways of 1923, the implementation of airport-area airspace control in 1969, and ultimately the extension of positive control to all “Class A” airspace between 18,000 and 60,000 feet [160]. Since this time, the FAA has dramatically improved the radar infrastructure, methods and computerized tools it uses to conduct ATM and implemented airspace structure throughout the country. Modernization efforts have continued in earnest through the FAA Next Generation Air Transportation System (NextGen) program, among others, however only modest airspace structural changes are being implemented through the NextGen Metroplex Airspace initiative [161].

Under the status quo, all vehicles operating in airspace over the United States, whether they be airplanes, helicopters or UAS, are expected to adhere to the relevant operational, airspace and ATM requirements promulgated by the FAA. Figure 66 displays the current airspace structure of the U.S. National Airspace System (NAS) notating the relevant ATM entities for each type of airspace. An aircraft entering one of the controlled airspaces must, at a minimum to gain access to that airspace, establish and maintain contact with the air traffic controller responsible for that airspace (except for VFR operations in Class E airspace). A variety of additional equipage and operational requirements may also apply for flight within specific airspaces.

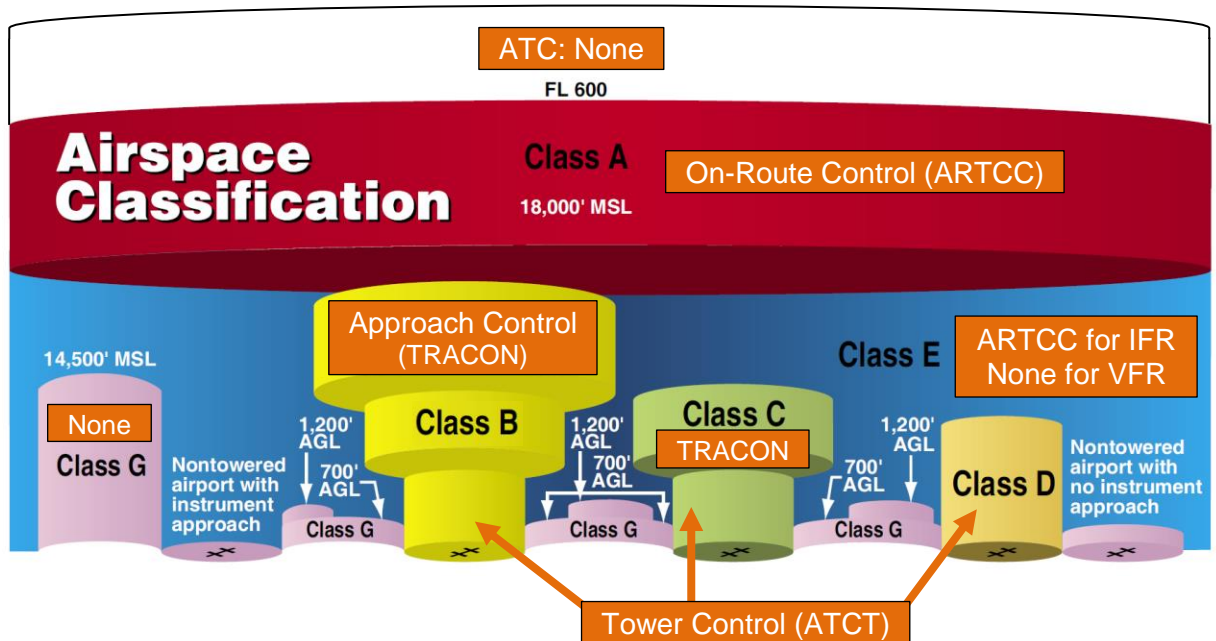


Figure 66. Airspace structure of the U.S. national airspace system with the compulsory air traffic control services for the airspace class indicated in orange. Image adapted from the FAA *Pilot’s Handbook of Aeronautical Knowledge* [162].

Medium and high altitude aircraft operations, which are assumed for this discussion as flight above a few thousand feet AGL (above ground level), follow a set of standards that is relatively homogenous around the U.S. independent of what lies beneath. On the other hand, low altitude

airspace operations (assumed for this discussion to be in the first few thousand feet) are managed by a set of standards that vary dramatically from location to location dependent upon people or property below, vehicle type and piloting best practices. The current rules for low altitude flight may be separated into three major categories relevant to this discussion of UAS and ODM Aviation:

1. Operating Altitude Minimums
2. Approaches to Aircraft Separation
3. Takeoff and Landing Locations

### **6.2.1 Operating Altitude Minimums**

The low altitude boundaries for flight are currently prescribed through minimum altitude requirements in § 91.119 of the Federal Aviation Regulations (FARs), which stipulates:

*Except when necessary for takeoff or landing, no person may operate an aircraft below the following altitudes:*

- (a) Anywhere. An altitude allowing, if a power unit fails, an emergency landing without undue hazard to persons or property on the surface.*
- (b) Over congested areas. Over any congested area of a city, town, or settlement, or over any open air assembly of persons, an altitude of 1,000 feet above the highest obstacle within a horizontal radius of 2,000 feet of an aircraft.*
- (c) Over other than congested areas. An altitude of 500 feet above the surface, except over open water or sparsely populated areas. In those cases, the aircraft may not be operated closer than 500 feet to any person, vessel, vehicle, or structure.*
- (d) Helicopters. Helicopters may be operated at less than the minimums prescribed in paragraph (b) or (c) of this section if the operation is conducted without hazard to persons or property on the surface. In addition, each person operating a helicopter shall comply with any routes or altitudes specifically prescribed for helicopters by the Administrator.*

The FAR above therefore stipulates that the relevant minimum altitude requirements vary based upon the type of vehicle being flown, the level of congestion of people and property underneath or near the flight, and the capacity of the pilot to land the aircraft in an emergency situation without causing undue hazard to bystanders and property. Perhaps most interestingly, subsection (d) of § 91.119 specifically exempts helicopters from all minimums except the safe emergency landing situation, provided the helicopter flight is conducted without causing hazard (but note, not necessarily avoiding noise annoyance) to individuals and property on the ground.

It should also be noted that the conditions necessary to qualify an areas as “congested” or “sparsely populated” are often determined on a case-by-case basis and are a subject of uncertainty among pilots. Varying interpretations of these terms by law firms and the FAA Office of the Chief Counsel provide a broad overview of this uncertainty among pilots and provide a sampling of some of the legal cases that originated as a result of this regulatory uncertainty [163], [164]. Ultimately, low-flying fixed-wing aircraft may be excluded from the areas the FAA and NTSB consider as congested. However, if UAS and ODM aircraft are treated as helicopters then the uncertainty of this regulation may not influence their operation.

Figure 67 presents a notional diagram displaying the status quo framework for low altitude flight as outlined by § 91.119. Note that fixed-wing vehicles are only able to fly below these minimum altitudes while landing or taking off, but helicopters may routinely fly in this airspace for other phases of flight.

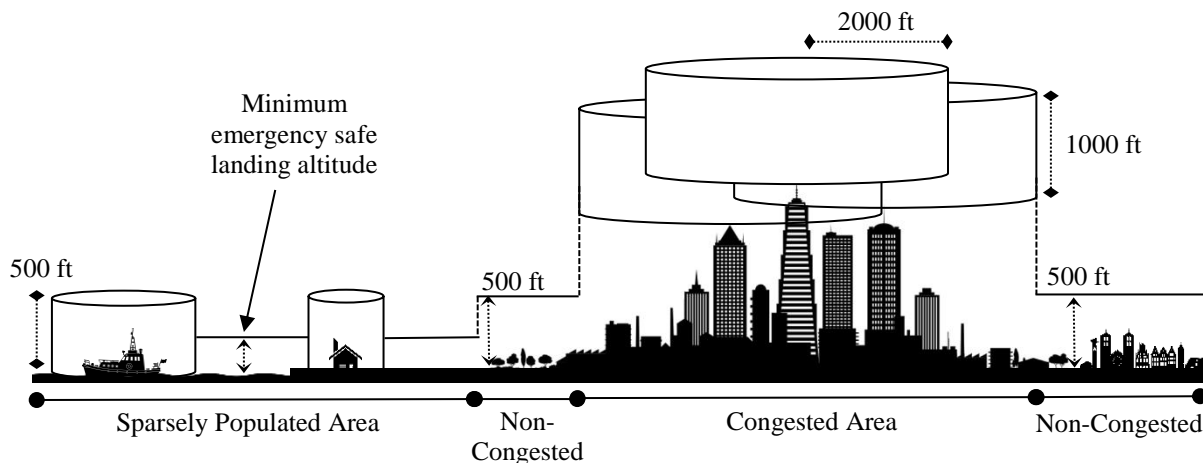


Figure 67. Status quo framework for aircraft flight minimums. Fixed-wing aircraft may not fly below these altitudes unless in an emergency, taking off or landing. Helicopters may fly below these altitudes as long as they maintain an emergency safe landing altitude and do not cause hazard to persons or property on the ground. *Image adapted from Obra Bajo: © BY-SA 3.0.*

## 6.2.2 Approaches to Aircraft Separation

Outside of controlled airspace, aircraft separation services are not provided by ATC and are the responsibility of the individual pilots through self-separation. When outside ATC, the first approach to self-separation assurance is cruising altitude stratification based upon flight direction. This approach applies to aircraft flying under Visual Flight Rules (VFR) above 3000 ft MSL, or aircraft flying under Instrument Flight Rules (IFR) above 2000 ft MSL (though all IFR flights are provided specific routings which may not follow these altitude separation standards).

For low altitude flight, however, aircraft self-separation through altitude stratification does not currently apply in most areas. Therefore, low altitude flight self-separation is maintained through lateral and longitudinal separation procedures and regulations. FAR § 91.111 provides the basic regulation stating that “no person may operate an aircraft so close to another aircraft as to create a collision hazard.” The regulation goes on to state that formation flight is possible if all pilots in command agree to the formation, but that formation flight is not possible if there are paid passengers onboard. FAR §91.113 rounds out the regulations stating that in good weather pilots are responsible to “see and avoid” and pass “well clear” of other aircraft.

The final low altitude separation approach for aircraft and helicopters specifies required or recommended time intervals between sequential landing or takeoff operations. Fixed-wing aircraft and helicopters generate wake vortices during flight that are potentially strong rotating volumes of air. Fixed-wing aircraft create a pair of counter-rotating vortices emanating from the wing tips or outboard flaps and trailing behind and down from the aircraft. Helicopters create strong rotor downwash that produce high velocity outwash vortices to a distance of approximately three times

the rotor diameter in all directions around the helicopter. In forward flight, helicopter downwash vortices transform into a pair of trailing vortices similar to those produced by aircraft [165].

Wake vortices may create dangerous flying conditions for vehicles traveling close behind or entering the landing area quickly after the departure of a previous aircraft. Trailing vortex strength increases with the mass of an aircraft or helicopter, and decreases with increasing speed. Therefore, special separation distances should be considered during takeoff and landing activities to avoid hazardous conditions due to wake vortex turbulence. FAA Advisory Circular 90-23G recommends detailed operational procedures to avoid wake turbulence encounters between various sizes of fixed-wing aircraft as well as helicopters.

In general, small aircraft should avoid taking off or landing immediately after larger aircraft by waiting two to three minutes for vortices to clear. They should then remain above the trailing vortices where possible. Little information is provided for helicopter operations, however fixed-wing pilots and helicopter pilots are advised to avoid operating within three rotor widths of another helicopter [166]. For operations in controlled airspace, standard air traffic control procedures (JO 7110.65W) require controllers to ensure a preceding helicopter has completely left the landing or takeoff area (either by flight or taxiing) before authorizing another helicopter to enter the area. Furthermore, controllers are also required to provide at least 200 feet of separation between simultaneous helicopter takeoff and landings [167]. These standards do not automatically apply to VFR operations outside of controlled airspaces.

Although the requirements or recommendations for aircraft separation are less well defined at low altitudes than at higher altitudes, they are currently well accepted in the status quo and provide for safe operation at the current flight densities. In areas that experience especially high density aircraft or helicopter operations, such as New York City, the FAA and local operators have established special operating procedures and communications frequencies to provide additional flight pattern control and support effective self-separation [168].

### **6.2.3 Takeoff and Landing Operations**

Under the current flight paradigm, aircraft and helicopters typically spend a majority of flight time well above the prescribed altitude minimums, and often well above low altitude airspace altogether. However, when involved in takeoff and landing phases of flight, aircraft are likely in closer proximity to bystanders and other aircraft than during any other phase of flight. As such, exemptions are made from many of the previously presented low altitude flight regulations, and additional standards come into force to provide for safe and responsible operation.

As presented in Section 6.2.1, § 91.119 exempts aircraft that are landing or taking off from the prescribed altitude minimums. Whether operating at an airport with controlled airspace or at an uncontrolled airport, pilots adhere to the set of published approach and departure procedures when operating IFR, and airport standards when operating VFR. These procedures or standards may specify appropriate descent path angles and altitudes on approach to the airport. They also specify traffic pattern information in the vicinity of the airport to enable more dense aircraft operations and support flight separation.

The landing of aircraft or helicopters at locations not designated as official airports or helipads is possible in many cases, but potentially subject to additional constraints such as local municipality

and state regulations, landowner preferences and law enforcement assessments of safety. Considering such factors, “off-airport” landings are often considered by pilots on a case-by-case basis to determine if such an operation is permissible with respect to all relevant authorities. As an example, Section 7.1.3.2 reviews the off-airport takeoff and landing restrictions ODM operators currently face in the Los Angeles region. Furthermore, Section 6.3.2 introduces some of the legal mechanisms landowners may use to prohibit or seek compensation for such off-airport operations near or above their properties.

#### **6.2.4 General Acceptance and Historical Challenges to the Status Quo Aviation System**

The regulations presented above have existed relatively unchanged for multiple decades and appear to have been sufficient to promote a high level of safety for low altitude aircraft operations, provide aircraft operators and clients with an acceptable level of utility, and satisfy the desire of bystanders on the ground for safety, privacy and comfort.

Challenges to the status quo have arisen from time to time primarily concerning either noise generation or privacy infringement by low flying private and government entities. Regarding noise, both legal and regulatory remedies have been pursued over the years. Noise has often been a central factor in legal cases concerning nuisance claims or government takings by landowners. Furthermore, congressional legislators passed the Los Angeles Residential Helicopter Noise Relief Act of 2013 in an effort to force the FAA pass regulations to reduce helicopter noise in L.A. [29]. The result of these efforts was the awarding of compensation to landowners impacted by noise, the creation of voluntary noise abatement procedures and helicopter routes, and the implementation of Temporary Flight Restriction (TFR) areas around particularly noise sensitive events.

Finally, some airports have also proactively addressed landowners’ right to be free from unreasonable noise by purchasing aviation easements above impacted land. The FAA and aircraft operators have also faced issues reactively through government takings (inverse condemnation), trespass and nuisance legal proceedings [169]. It should be noted that aviation easements often place restrictions on the utilization or development of the underlying property. This limitation has led to a host of additional legal challenges and concerns; these challenges shall not be considered in this section as they do not impact how current or future vehicles will operate at low altitudes.

The second common historical challenge to the status quo were privacy concerns resulting from low altitude flight over private land. Over the years the courts have handled numerous cases where private citizens and corporations have questioned the legality of aerial surveillance gathering. Legal action was taken to this effect typically questioning the admissibility of evidence collected in this way, or through filings for trespass or nuisance tort action. As will be discussed further in Section 6.3, these cases often resulted in the confirmation of pilots’ rights to operate in accordance with FAA regulations rather than confirming or expanding landowners’ rights.

#### **6.2.5 Impending Challenges to the Status Quo Aviation System**

The widespread adoption of UAS and ODM aircraft is likely to increase the number of vehicles operating well beyond the conditions outlined in this review of the status quo aviation system. UAS and ODM aircraft will frequently (or perhaps always, in the case of UAS) operate below the



operating altitude minimums for fixed-wing vehicles. These new vehicles will also likely operate at densities that stress current aircraft separation standards. Both types of vehicles may frequently conduct off-airport takeoff and landings, and the increased density of these vehicle flying at low altitudes may exacerbate community noise and privacy concerns. Considering these possibilities, ODM aviation and UAS services are likely to face new policy and legal uncertainties not experienced by operators in the status quo system.

### ***6.3 Policy and Legal Uncertainties Concerning Low Altitude Aviation***

The fundamental policy and legal uncertainty concerning low altitude aviation is the question of how the right of an aircraft (or UAS) pilot to operate in low altitude airspace will be balanced with the property rights of landowners below. The national airspace in the U.S. is considered a *regulated commons* in which the public is free to operate at will provided they meet the set of usage requirements set forth by the FAA to ensure efficient and safe usage of the airspace. The surface, on the other hand, is split into private property parcels with precise demarcations and reserved usage rights for the landowner.

The different governance systems of these two domains intersect at some point in low altitude airspace. The status quo policies and regulations do not sufficiently reconcile these governance structures. As a result, it is unclear which governance system is in force for the lowest few hundred feet of airspace above the ground. This uncertainty in the regulations has resulted in government takings, privacy and nuisance claims by landowners in the past. The courts may experience a resurgence of such cases in coming years if UAS and ODM Aviation operations increase flight densities in low altitude airspace and there is no timely legislative clarification.

The minimum operating altitudes, separation standards, and landing and takeoff regulations presented in Section 6.2 form the bulwarks of current low altitude aircraft operations. While not explicitly resolving the conflict of pilot and landowner usage rights, an equilibrium has been reached in the status quo system where pilots have nearly unlimited protected rights to fly above the FAA defined minimum altitude limits, and airports constantly work to balance the rights of the flying and non-flying public for takeoff and landing operations occurring below these minimum altitudes. Before the widespread availability of commercial and private UAS, these regulations for the most part were sufficient to balance the concerns and rights of the non-flying public with aircraft operators.

The perceived policy and legal uncertainties in low altitude airspace flight and ground ownership rights may be decomposed into two simple questions as shown in Table 35 and Table 36 at the beginning of this chapter:

1. Who has ownership and regulative authority of low altitude airspace?
2. How are landowners' rights balanced with a citizen's right to flight and use of the national airspace?

This subsection will explore each of these questions. Relevant FAA regulations, supported by the interpretations of federal and state case law and enhanced through the discussions of legal scholars, are summarized to provide readers with an understanding of the context surrounding each of these questions. It should be emphasized that there is significant legal uncertainty concerning these subjects, particularly with respect to UAS. It is therefore inevitable U.S. courts will face numerous

cases of first impression concerning low altitude UAS operations in the forthcoming years that will address the legal uncertainties presented herein.

Figure 68 displays the fundamental structure of the regulatory, legal and judicial process aviation regulations and allowable flight operations are determined through. This thesis seeks to answer the two questions presented above by first reviewing the constitutional and statutory mandates behind the FAA’s regulations. This review addresses Congress’ intentions for airspace ownership and regulation, and also assesses if the federal government may preempt (overrule) local and state regulations concerning operations in low altitude airspace. Next, this thesis reviews the relevant case law to identify how relevant regulation and statutory law has been interpreted by the courts.

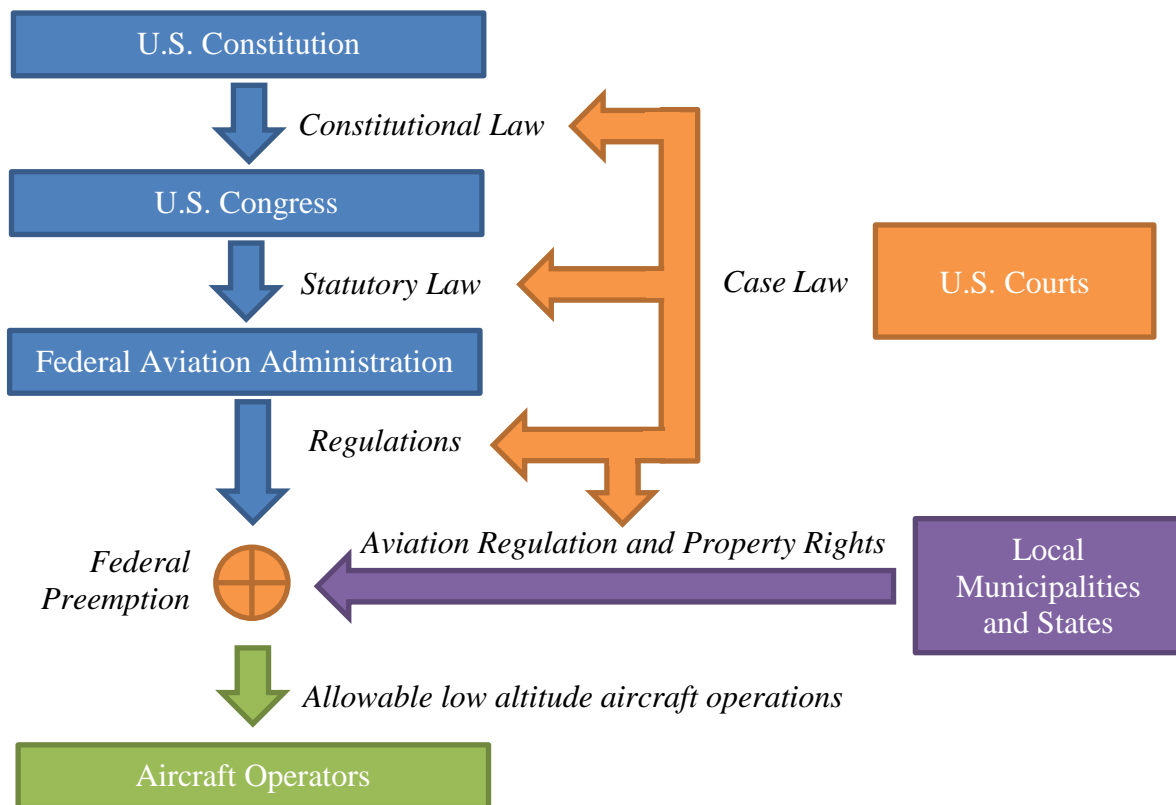


Figure 68. This thesis shall methodically review the legal process for the development of aircraft operating regulations including U.S. federal law, judicial case law and federal preemption to determine what low altitude aircraft operations may be allowable for UAS and ODM aircraft.

### 6.3.1 Who Has Ownership and Regulative Authority of Low Altitude Airspace?

Establishing clear ownership and regulative authority of low altitude airspace is paramount to determining who has the right to control aircraft operations in that airspace. As suggested in Figure 66 and reasserted in recent statements, the FAA claims responsibility for U.S. airspace all the way down to the surface [170]. The FAA has reiterated its legal responsibility for low altitude airspace as an effort to preempt state and local governments from developing their own regulations that prohibit or limit low altitude aircraft (and UAS) operations in their area [171].

The statutory mandate for this claim may be found in Title 49 of the United States Code (U.S.C.) § 40103(a)(1). In this statute the United States Government, and its subsidiary the FAA, is granted “exclusive sovereignty of airspace of the United States.” § 41713(b)(1) goes further to explicitly clarify Congress’ intent for air transportation to be completely under the sole purview of the FAA by stating “except as provided in this subsection, a State, political subdivision of a State, or political authority of at least 2 States may not enact or enforce a law, regulation, or other provision having the force and effect of law related to a price, route, or service of an air carrier that may provide air transportation.” The constitutional authority to provide the express preemption of state ownership of airspace and operations through these statutes is derived from the Commerce Clause of the Constitution (Art. 1, §8, cl. 3).

While these statutes appear at first glance to assign jurisdiction of *all* U.S. airspace to the FAA, there are a variety of complexities that must be considered when specifically assessing low altitude airspace and the potential operation of ODM aircraft or UAS within these airspaces. First, some scholars have suggested that the federal government (and thus the FAA) may not have authority under the Commerce Clause to preempt state regulation of UAS operations in low altitude airspace as a majority of such operations are very short range, and therefore unlikely to cross state borders [172], [173].

Investigating § 41713(b) further, it can be seen that Congress may have already set a precedent for such limitations of the Commerce Clause in cases of purely *intrastate* air transportation. The second paragraph, § 41713(b)(2), reads “paragraphs (1) and (4) of this subsection do not apply to air transportation provided entirely in Alaska unless the transportation is air transportation (except charter air transportation) provided under a certificate issued under section 41102 of this title.” While this paragraph clearly does not give the state government of Alaska full authority to regulate the operations of all intrastate operators, it does suggest there is a potential for Alaska or other states to petition the FAA for regulatory control of low altitude air transportation operations contained completely within their borders. In this case, future ODM Aviation or UAS operators may be subject to both federal and state regulations on their operations.

While § 41713(b)(2) potentially provides states with a line of argument to regulate intrastate UAS or ODM Aviation operations, the federal government may have a different pathway to preempt state regulation via the Commerce Clause. One such method would be to argue federal control of low altitude airspace is necessary to ensure the safe and efficient operation of the interstate air transportation operations occurring at higher altitudes and around airports. The FAA has adopted such a position in saying local municipality regulation of UAS could result in a “patchwork quilt of differing restrictions [that] could severely limit the flexibility of the FAA in controlling the airspace and flight patterns, and ensuring safety and an efficient air traffic flow” [174]. While such an argument has been rather straight forward for historical operations and is well supported in FAA publications by a plethora of case law [174], the FAA may have a more difficult time showing evidence that low altitude operations of UAS or ODM aircraft well away from airports influence interstate transportation safety and efficiency.

A second potential approach for the federal government to invoke the Commerce Clause is simply to display that although the actual missions of a UAS or ODM aircraft may be within a single state, the goods or persons they convey may be “brought from, or eventually be destined to go to, another state.” This language, from 33 CFR §329.6(b) has been used to categorize marine transportation

on bodies of water completely contained within a single state as interstate transportation; it is likely a similar line of reasoning would apply to air transportation. Supreme Court Justice Hugo Black expressed this exact impression in his dissent to *United States v. Causby* where he stated, "...the Commerce Clause of the Constitution gave Congress the same plenary power to control navigable airspace as its plenary power over navigable waters" (328 U.S. 256 (1946)).

ODM Aviation operations and many commercial UAS applications may fall under sole FAA regulatory authority due to the two arguments presented above. However, the authority of the FAA to regulate private or commercial UAS operating within a few tens of feet of the ground multiple miles from an airport may not meet the requirements of the Commerce Clause. In fact, in a 2014 dispute between the FAA and a Virginia based commercial drone operator, it was reported that "an administrative law judge for the National Transportation Safety Board expressed skepticism that the FAA presently had regulatory power over such flights" [175].

Although 49 U.S.C. § 41713 may enable states some regulative authority over intrastate aircraft operations and reinforces FAA control of others, the section does not address who owns the airspace. Clarifying ownership (rather than regulative authority) of airspace is critical as this will determine if, and up to what altitude, an owner may pursue property torts or seek government takings claims against aircraft operations occurring in their "private" airspace. In order to address the question of ownership of airspace, a more detailed investigation of § 40103 and the relevant case law is in order.

Congress explicitly gives U.S. citizens "a public right of transit through the navigable airspace" in § 40103(a)(2) and directs the FAA to "develop plans and policy for the use of the navigable airspace...to ensure the safety of aircraft and efficient use of airspace" in § 40103(b)(1). Finally, Congress mandates the FAA "shall prescribe air traffic regulations... (including regulations on safe altitudes)" in the next paragraph with the added goal of protecting individuals and property on the ground. When considered as a whole, these regulations may be taken to establish the "navigable airspace" above the United States as a regulated commons that is owned by no one, managed by the FAA, and accessible to anyone who follows the FAA's rules [175].

Accepting this interpretation, the question of airspace ownership now revolves around what is defined as "navigable airspace" and considered owned by no one, and what part of the low altitude airspace, if any, is below navigable airspace and may be considered the property of the landowner. While not directly defining airspace in § 40102, the term "navigable airspace" is defined in § 14 CFR 1.1 (and similarly in 49 U.S.C. § 40102(a)(32)) to be "airspace at and above the minimum flight altitudes prescribed by or under this chapter, including airspace needed for safe takeoff and landing" Revisiting Figure 67, it can be seen that by this definition navigable airspace varies in altitude dependent upon persons and property beneath the flight, but at a minimum reaches down to the minimum emergency safe landing altitude prescribed for fixed-wing aircraft in sparsely populated areas or over open water.

As a note, although § 91.119(d) enables helicopters to fly beneath these operating altitude minimums provided the operation is conducted safely, the regulation has generally been interpreted to not expand navigable airspace to these flight levels below the operational altitude minimums defined for fixed-wing aircraft [176]. Similarly, although not explicitly stated in the regulations, off-airport takeoff and landings by helicopters are also considered operations outside

of the navigable airspace. Supporting these interpretations, the Supreme Court ruling in *Florida v. Riley* specifically confirmed that a helicopter flying at 400 ft over a home in a rural area was below the navigable airspace, yet a legal operation as it met all FAA regulations (488 U.S. 445).

Therefore, the review of statutes and regulations concerning airspace ownership and regulatory control up to this point was summarized through Table 37.

Table 37. Airspace ownership and regulatory authority as derived from current statutes and regulations.

| <b>People/Property<br/>Beneath</b> | <b>Navigable<br/>Airspace<br/>Boundary<br/>(NAB)</b> | <b>Airspace<br/>Ownership<br/>Below<br/>NAB</b> | <b>Airspace<br/>Ownership<br/>Above<br/>NAB</b> | <b>Airspace<br/>Regulation<br/>Below<br/>NAB</b> | <b>Airspace<br/>Regulation<br/>Above<br/>NAB</b> |
|------------------------------------|--|---|---|--|--|
| Open water/sparsely populated land | Min. emergency safe landing alt.                     | ?   | commons   | FAA/State?                                       | FAA  |
| Non-congested areas                | 500 ft   | ?   | commons   | FAA/State?                                       | FAA  |
| Congested areas                    | 1000 ft  | ?   | commons   | FAA/State?                                       | FAA  |
| Takeoff & Landing                  | SFC to 1000 ft                                       | ?   | commons   | FAA  | FAA  |

Viewing Table 37, uncertainty in the regulations may clearly be seen concerning who has ownership of airspace below the navigable airspace. To a lesser degree, there also exists a legal question concerning if the states have some regulatory privileges over aircraft operations in the airspace below navigable airspace. The legal question of regulatory privilege has already been addressed to some degree and does not necessitate further investigation for the purposes of this thesis.

Low altitude airspace ownership below the navigable airspace may have profound impacts upon the ultimate operation of UAS or ODM Aviation networks. Considering this, a summary of the relevant case law concerning low altitude airspace ownership is provided below in an effort to present the complexity of this regulatory uncertainty. Furthermore, it is apparent there has been an intentional abstention on behalf of the legal system to close this regulatory uncertainty through case law, perhaps showing deference to lawmakers on this dramatic property rights entitlement issue.

The case of first impression that addressed low altitude airspace ownership by landowners was *United States v. Causby* in 1946. Sparing the details of the case, Causby sued the government arguing that military aircraft flying as low as 83 feet over his property had made his property unsuitable for farming chickens (many had died as a result of the aircraft noise) and represented a taking of his property by the government under the Fifth Amendment. In its ruling, the Supreme Court established numerous significant precedents:

1. The Court abolished the common law doctrine of *Cujus est solum, ejus est usque ad coelum (et ad inferos)*, or “Whose is the soil, his it is up to the heavens (and down to hell)” [177]. This effectively removed any de facto private ownership claim of airspace at all altitudes and especially of navigable airspace as defined at that time.

2. The Court confirmed that airspace at and above the minimum safe altitudes of flight set by the FAA is “a public highway, and part of the public domain.” This confirmed that navigable airspace is defined by the FAA, and is a commons owned by no one and open to flight subject to the regulations of the FAA.
3. Third, and perhaps most significantly, the Court stated “flights over private land are not a taking, unless they are so low and frequent as to be a direct and immediate interference with the enjoyment and use of the land.” In finding this, the Court set the precedent that low altitude operations *could* be considered a taking of property by government, or a trespass by non-government aviators [175].

In this ruling, the Court implied the existence of some amount of “superadjacent” (overlying) airspace owned by the landowner where they could exclude aircraft operations. However, the Court refrained from specifying the altitude landowner property rights extended to and instead only offered the guidance that the landowner controlled “at least as much of the space above the ground as he can occupy or use in connection with the land” and “the immediate reaches of the enveloping atmosphere.” Furthermore, the Court established that landowners owned this nebulous amount of airspace whether or not they physically occupied it (through means of a building, for example), and simply had to show the airspace was necessary for their use and enjoyment of the land. Therefore the Court confirmed that landowners did own some amount of airspace, but shrouded the issue in uncertainty by not defining how much airspace they owned.

4. At the time of the *Causby* ruling, the aeronautical regulations did not define navigable airspace to include airspace necessary for takeoff or landing. Therefore, the Court stated that the military flights over the Causby farm were below the minimum safe flight altitude and therefore outside the navigable airspace considered as public domain by Congress. Foreseeing that Congress or the FAA may lower the minimum safe altitudes or change the definition of navigable airspace (which indeed occurred shortly after), the Court went on to proffer “if any airspace needed for landing or taking off were included [as navigable airspace], flights which were so close to the land as to render it uninhabitable would be immune” but “there would be a taking.” In other words, the Court recognized the authority of the FAA or Congress to define navigable airspace all the way to the ground around airports and operate aircraft in this airspace without violating property owners’ rights. However, the Court asserted that to do so the FAA would have to recognize a taking of property had occurred and compensate the landowners around the airport for the reduced value of their property due to the operations.

Finally, in this fourth statement the Court also recognized the authority of the FAA to lower the minimum safe altitude standards (perhaps due to new technologies or aircraft), but added the qualification in dicta that “if [the FAA] prescribed 83 feet as the minimum safe altitude, then we would have presented the question of the validity of the regulation.” The exact meaning of this statement is open to interpretation, but it implies that navigable airspace may be expanded downward by the FAA, but the courts may subject such new regulations to greater scrutiny to determine if the regulated safe minimum altitudes are valid.

Through these four findings and their associated discussion *Causby* established the foundation for legal property-based challenges of airspace intrusions. However, although the case firmly stated landowners do have claim to some amount of airspace immediately above their property, the lack of definition as to the exact reach of this private airspace left many questions for later courts to consider. A 2013 Congressional Research Service (CRS) review of airspace legal issues posed these four questions that resulted from *Causby* [176]:

1. Where is the dividing line between the “immediate reaches” of the surface and public domain airspace?
2. Can navigable airspace intersect with the “immediate reaches” belonging to the private property?
3. Can aircraft flying wholly within navigable airspace, as defined by federal law, ever lead to a successful takings claim?
4. How does one assess claims based on lawfully operated aircraft, such as helicopters, flying below navigable airspace?

Subsequent court cases concerning trespass, nuisance and government takings, among others, sought to interpret and apply the rulings of *Causby*. A review of the key facts of these cases is presented in Table 38 and discussed further below. While these additional cases may potentially be seen to clarify some of the questions presented above, by and large airspace ownership and the rights of pilots versus landowners in low altitude airspace remains a murky legal area. As evidence of this, in 2013 the CRS explored multiple “post-*Causby* theories of airspace ownership” that either federal or state courts have expressed over the past half century [176]; many of these theories and the resultant rulings set dramatically different standards for airspace ownership and the associated rights of aircraft operators and landowners.

It is appropriate at this time to address the common public misconception that after the Supreme Court’s *Causby* ruling a lower court established a definitive altitude describing the upper limit of private airspace. Following *Causby*, the Supreme Court sent the case to the Court of Claims with instructions to specify the “nature or duration of the easement” taken by the government for the military flights so that appropriate financial compensation could be made to the Causbys. The Court of Claims then revisited the case in 1948 and determined that the easement extended up to 365 ft because this was the height of the tallest tree on Causby’s property (65 ft) plus the 300 ft minimum safe altitude for flight of aircraft as defined by the Civil Aeronautics Authority in 1948 (75 F.Supp. 262 Cl. Ct. (1948)).

This ruling by the Court of Claims did not set a universal demarcation altitude of private airspace at 365 ft, but rather explicitly stated in the finding that the height of such an easement would vary from case to case dependent upon the use of the land. Therefore the ruling should not be considered outside the scope of the *Causby* case except as guidance for defining such easements or awarding nuisance damages.

Moving beyond this, three main takeaways should be gathered from the review of key cases in Table 38. First, the Supreme Court confirmed in *Braniff* and *Griggs* that landing and takeoff operations at low altitude, even if in navigable airspace, were a takings. This implies that it may be possible for low altitude flights other than takeoff or landings to be considered a takings as well, even if they occur above the prescribed operating altitude minimums. Secondly, the cases show

that the Supreme Court has given no credence to a specific “fixed height” altitude delimiting private and public airspace even though some other federal courts have. Third, the number of cases largely diminished with time as the status quo of manned aviation operations became acceptable to the public [178]. However, low altitude airspace ownership questions have recently resurged in response to UAS activities.

Table 38. Summary of key court cases concerning low altitude flight and property rights.

| <b>Case</b>  | <b>Date</b> | <b>Summary</b>  |
|--|-------------|---|
| <i>Braniff Airways v. Nebraska State Board of Equalization &amp; Assessment</i> (347 U.S. 590) | 1954        | The Supreme Court, in dicta, refrained from clarifying if a takings could occur for flights occurring entirely in navigable airspace (landing and takeoff paths were not yet considered navigable airspace).  |
| <i>Highland Park Inc. v. United States</i> (161 F.Supp. 597)                                   | 1958        | U.S. Court of Claims found the flight of new vehicles (such as heavy jet airplanes) in airspace previously used by other aircraft (such as propeller-driven aircraft) may constitute a new taking if the operation substantially interferes with the use and enjoyment of the surface of the ground in a way the previous operations did not. |
| <i>Griggs v. Allegheny County</i> (369 U.S. 84, 90)  | 1962        | The Supreme Court held that low altitude flight over private property on departure from an airport, although now defined as navigable airspace, constituted a taking by the government.   |
| <i>Aaron v. United States</i> (311 F.2d 798)   | 1963        | The U.S. Court of Claims found that jet flights above 500 ft in non-congested areas were in navigable airspace and immune from legal action even if they cause inconvenience to the landowner beneath, but flights below 500 ft should be considered a takings.   |
| <i>Powell v. United States</i> (1 Cl. Ct. 669)   | 1983        | The U.S. Claims Court confirmed flights above 500 ft in uncongested areas may not be considered intrusion upon the property beneath.  |
| <i>Boggs v. Merideth</i> (3:16-cv-6-DJH)   | 2016        | Defense sought declaratory judgment from the U.S. District Court in western Kentucky to clarify private property rights and right to traverse airspace for UAS in support of their client who shot down a drone over his property. The incident occurred prior to the FAA release of the small unmanned aircraft regulations.                 |



The current state of the law concerning low altitude airspace ownership may best be summarized as follows.

- There is not currently a definitive altitude that separates landowner private airspace from public airspace. However, flight in navigable airspace above the current altitude minimums has typically been considered protected from government takings claims.
- “As the height of the overflight increases... the Government’s interest in maintaining air sovereignty becomes weightier while the landowner’s interest diminishes, so that the damage showing required increases in a continuum toward showing absolute destruction of all uses of the property” (Stephens v. United States, 11 Cl. Ct. 352 (1986)).
- To address this continuum, the Federal Circuit Court of Appeals may use a three-step test to assess whether a government takings has occurred [173]:
  - i. Whether the planes flew directly over the plaintiff’s land
  - ii. The altitude and frequency of the flights
  - iii. Whether the flights directly and immediately interfered with the plaintiff’s enjoyment and use of the land

As UAS and ODM Aviation seek to make greater use of low altitude airspaces, the murky legal situation of airspace ownership and regulatory authority will become a more pronounced issue. Greater detail on low altitude airspace ownership legal questions may be found in the following articles:

1. The State of Drones: State Authority to Regulate Drones. *Albany Government Law Review* [173].
2. Airspace in an Age of Drones. *Boston University Law Review* [175].
3. Integration of Drones into Domestic Airspace: Selected Legal Issues. *Congressional Research Service* [176].

### **6.3.2 How are Landowners’ Rights Balanced with a Citizen’s Right to Flight and Use of the National Airspace?**

A 2014 Pew Research Center study found that the most common public concerns regarding low altitude airspace operations are safety and the associated laws and regulations controlling flight operations [179]. The uncertainties in these laws and regulations were addressed in Section 6.3.1. According to the study, the next most common public concern is privacy. This subchapter provides a brief review of the relevant legal cases that discuss the relationship between a pilot’s right to flight, the media or government’s right to collect information, and a landowner’s right to privacy and enjoyment of their property.

Private individuals (and companies) are granted rights under state law to protect themselves and their property against many potentially undesirable actions on the part of others. These protections are often contained within state “tort claims” and include, but are not limited to:

- Trespass: knowingly entering another person’s property without permission
- Nuisance: Substantial and unreasonable interference of an individual’s enjoyment of their property through a thing or activity

- Voyeurism: sexual interest in or practice of spying on individuals (peeping Tom)
- Invasion of Privacy: intrusion into the personal life of another, without just cause, such as intrusion upon seclusion/private affairs or the public disclosure of embarrassing private information

The federal cases presented in the previous sub-section serve as precedents for state courts to adjudicate tort claims against citizens or companies. Therefore, this subchapter will review how the legal uncertainties from the federal level may appear in state tort claims concerning low flying UAS and ODM aircraft, and what differences may exist, if any.

#### 6.3.2.1 *Trespass*

Section 159 of the Second Restatement of Torts asserts that an actionable trespass occurs if an aircraft “enters into the immediate reaches of the air space next to the land, and it interferes substantially with the [owners] use and enjoyment of his land.” Since federal courts and legislators have failed to define the extent of private airspace ownership, state courts have also considered this subject in order to adjudicate trespass cases. Once again, the Second Restatement of Torts offers guidance for such cases through comment “L” (pg 283-284) where it suggests flights over 500 ft are likely not in private airspace, while flights under 50 ft mostly likely are, and flights at 150 ft depend upon the circumstances of the operation. For a successful trespass claim, the plaintiff must not only show that an aircraft entered their airspace, but that it also substantially diminished their use or enjoyment of the land.

In the case of UAV and ODM aircraft, infrequent flights over an individual’s property, even if at relatively low altitudes, may not represent an actionable trespass tort as they are unlikely to cause substantial loss of enjoyment of the land. Landing a UAS or ODM aircraft on a neighbor’s property would also be un-actionable as trespass if the vehicle descended directly from navigable airspace into the neighbor’s airspace and property and did not pass into another’s airspace.

#### 6.3.2.2 *Nuisance*

Nuisance, on the other hand, is likely to be more commonly applied to aircraft operations at low altitudes. A nuisance tort is not based upon property (or airspace) ownership and simply requires that a flight creates a substantial and unreasonable interference of the landowner’s enjoyment or use of their property.

The definition of substantial and unreasonable is up to the courts to interpret, however the 2013 CRS report suggested that the reduced noise, size, vibrations and dust disturbance of UAS (and likely electric ODM aircraft) as compared to helicopters and conventional aircraft may make them less likely to qualify as a nuisance claim at reasonable flight altitudes [176]. On the other hand, the authors also noted that if UAS flights occur at significantly greater density than current operations, then this may constitute a new form of unreasonable interference. Furthermore, because private airspace entrance is not required, UAS or ODM operations in a neighboring airspace may constitute a valid nuisance tort, even if that airspace is owned by a neighbor or is public airspace.

### 6.3.2.3 *Voyeurism*

Laws protecting citizens from voyeurism vary from state to state. Where such laws exist, they are often quite similar to those protecting individuals from an invasion of privacy, therefore a discussion of low altitude airspace property rights concerning voyeurism shall be reserved for the next sub-section. However, federal law also prohibits certain types of voyeurism on federal property through 18 U.S.C. § 1801. While this section does not currently apply to federally controlled airspace, Congress could enact such a regulation [176].

### 6.3.2.4 *Invasion of Privacy*

While landowners often object to the noise, lights and disturbance caused by low flying large aircraft, the primary concerns for quieter and smaller UAS or future ODM aircraft are privacy and disturbance of seclusion. While trespass and nuisance torts handle disturbance of seclusion succinctly, tort law concerning privacy matters is far more complex in the case of low altitude flight. Furthermore, the existing case law for low altitude aviation privacy infringement is separated into separate categories of law: “unreasonable search” when government actors conduct aerial surveillance, and “invasion of privacy” when private actors conduct aerial surveillance. For the purposes of this review of privacy law with respect to low altitude airspace, these two fields of case law shall be considered jointly as the ultimate assignment of wrongdoing is frequently dependent upon the same rationale in both cases.

Table 39 presents five cases that review how low altitude aircraft operations may be susceptible to invasion of privacy or unreasonable search claims. The cases presented appear to provide general precedent enabling the flight of helicopter-type aircraft down to at least 400ft, and perhaps as low as 126 ft without constituting an invasion of privacy.

Considering these cases, ODM aircraft or UAS passing over private property or infrequently landing in adjacent property are unlikely to be subject to invasion of privacy action. In fact, it is a common event in many cities around the United States for news gathering or police helicopters to fly or even hover at a few hundred feet over private property and collect imagery and sound. There are a plethora of nuisance claims against such operations, but few privacy complaints. However, frequent ODM or UAS operations, especially if the intended purpose of the flight is sightseeing or surveillance, may trigger renewed privacy concerns. Furthermore, many of the cases presented protect only “naked-eye” surveillance and courts would have to reconsider such precedents with respect to advanced imaging technologies [180].

Greater detail on low altitude airspace privacy legal questions may be found in:

1. Observations from Above: Unmanned Aircraft Systems and Privacy. *Harvard Journal of Law and Public Policy* [180].

Table 39. Summary of key court cases concerning low altitude flight and privacy rights.

| Case  | Date | Summary   |
|---|------|---|
| <i>McClain v. Boise Cascade Corp.</i> (271 OR 549, 556)   | 1975 | The Oregon Supreme Court held privacy of the home or property is not protected if it can be viewed readily from a publically accessible road.   |
| <i>Dow Chemical Co. v. United States</i> (476 U.S. 227, 229)                                    | 1986 | The Supreme Court held that EPA surveillance of private land from an aircraft at 1200 ft was not an invasion of privacy as the land was “open to the view... of persons in aircraft lawfully in the public airspace.”                                   |
| <i>California v. Ciraolo</i> (476 U.S. 207)   | 1986 | The Supreme Court held that police surveillance from an aircraft at 1000 ft above private property did not violate a “reasonable expectation of privacy” as it considered open-access navigable airspace a “public vantage point.”                      |
| <i>Florida v. Riley</i> (488 U.S. 445)  | 1989 | The Supreme Court held that police surveillance from a helicopter at 400 ft above private property, even though below navigable airspace, was not an invasion of privacy as any “member of the public could legally have been flying” in that airspace. |
| <i>GTE Mobilnet of South Texas, LTD. Partnership v. Pascouet</i> (61 S.W. 3d 599, 605 Tex. App) | 2001 | A Texas Court of Appeals held that maintenance workers attending to a 126 ft cell phone tower adjacent to private property was not sufficiently offensive to be an invasion of privacy.   |

#### **6.4 Impact of Policy and Legal Uncertainties on UAS and ODM Aviation**

A 2014 Pew Research Center study found that 63% of Americans “think it would be a change for the worse if *personal and commercial drones are given permission to fly through most U.S. airspace*” [181]. It is not far-fetched to project that a similar percentage of Americans may also negatively view the appearance of ODM aircraft in most U.S. airspace. However, the lack of association of ODM Aviation with military applications may result in a more favorable acceptance of the technology. Also potentially supportive for ODM operations, the same Pew Research study found that the number one “futuristic innovation” the American public would like to own is “travel improvements like flying cars and bikes.”

Although lacking the military connotation of UAS and desired as a concept by many Americans, ODM Aviation is likely to stimulate the same visceral concerns citizens have with UAS. A recent technoethical review of commercial drone literature between 2010 and 2015 found that the most frequently cited concerns for commercial UAS usage were safety of those on the ground, and effective law and regulation to protect the rights of those on the ground; privacy concerns ranked third [179].

These figures are significant because law and regulation are borne out of the confluence of business influence and public perception. In the case of low altitude aviation, the largely negative slant of

public perception to UAS (and potentially ODM Aviation) creates a substantial threat that the legal and policy uncertainties identified in Section 6.3 may be resolved by giving extensive rights to landowners; this could stifle the potential extent of the new UAS and ODM industries. While current-day aircraft operations in navigable airspace around airports or above the operating altitude minimums are relatively well accepted, significant increases of flight density as a result of ODM Aviation or UAS activities could renew legal attacks on such operations. Furthermore, UAS operations in the airspaces *below* current navigable airspace are already under intense fire with 45 states considering 168 bills affecting UAS flight in 2015 alone [171].

This sub-section ruminates upon potential limitations of aircraft operations in low altitude airspace that may be possible as a result of the identified legal and regulatory uncertainties.

#### **6.4.1 Potential Limitations on Operations below Historical “Navigable Airspace”**

The ODM Aviation and UAS industries are perhaps most vulnerable to the legal and regulatory uncertainties presented in Section 6.3 with respect to their right to operate vehicles in low altitude airspaces historically not considered “navigable airspaces.” Currently, helicopters operate at low altitudes outside of navigable airspace according to FAA safety standards and a set of best practices intended to protect the operator from privacy or nuisance lawsuits. Similarly, UAS are operated below 400 ft according to the FAA standards laid out in 14 CFR Part 107. Potential limitations on future operations in these low altitude airspaces are dependent upon how the legal and regulatory uncertainties presented above are interpreted or resolved. The actual future scenario for low altitude airspace is likely to be a combination of the situations presented in the following subsections.

##### *6.4.1.1 FAA as the Sole Aircraft Operations Regulator*

One potential situation is that the courts will definitively confirm the FAA’s domain over U.S. airspace and its right to regulate aircraft operations all the way to the surface. In this situation ODM aircraft, if considered as helicopters for regulatory purposes or given a new tiltrotor certification, will be able to fly below navigable airspace under similar operational rules as helicopters today. UAS will also experience gradually expanded airspace access and more expansive operational allowances based upon maturing capabilities or technologies. The FAA will ensure there are consistent regulations across the United States for low altitude flight.

If aircraft operations become significantly more dense in the future, the FAA would also have the authority to implement new air traffic management approaches to ensure safety. Finally, ODM aircraft and UAS would still be susceptible to FAA sanctions for operating in a dangerous manner, or to municipal nuisance and privacy tort laws. Even if the FAA were to lower the minimum safe operating altitudes or create a new class of low altitude navigable airspace for UAS and ODM operations, this would not necessarily protect such operations from tort cases and may even be viewed as a takings by the FAA under the Fifth Amendment (see *Braniff, Griggs and Aaron*).

##### *6.4.1.2 State or Local Municipalities Obtain Regulatory Control of Operations below Navigable Airspace*

The FAA’s regulatory response to the rapid appearance of commercial and private UAS in the United States has frequently been criticized as unduly slow, insufficient in its protections of the

public, and restrictive to the burgeoning industry [182]. Feeling the pressure of the UAS regulatory uncertainty before Part 107 was issued, 20 states enacted legislation to regulate drone use in 2015. While some of these laws are in traditional areas of state power such as limiting police usage of UAS, prohibiting UAS assisted voyeurism, or prohibiting the weaponizing of UAS, some of them are beyond standard state powers and attempt to regulate UAS operations or prohibit access to certain airspaces. These laws invoke the legal question of federal preemption of aircraft operation regulations [171]. As discussed in Section 6.3.1, states may have a legal claim to regulative authority for non-navigable, low altitude airspace as operations in these regions will almost certainly be intrastate.

If courts bestow state and municipal governments with regulatory authority over flights in regions below navigable airspace, a “patchwork quilt” of different low altitude operating regulations could emerge. In this case, low altitude operators may potentially have to contend with different altitude, speed, weight and permissible time of day requirements between neighboring municipalities. As operations become more dense, ATC in the low altitude airspaces could also be managed differently by different municipalities. Due to these reasons, many authors and the FAA have stated that while they believe local municipalities should regulate in areas such as privacy, nuisance or infrastructure zoning, their regulation of the aircraft operations in low altitude airspace could harm the industry and reduce safety.

In perhaps the most well know current example of state regulation of aircraft operations in low altitude airspace, the Oregon state legislature passed a law in 2013 giving landowners the right to tort action against individuals operating UAS at less than 400 ft over their land, assuming the flight was repeated after the pilot was notified to desist (OR Rev Stat § 837.380). While not necessarily granting landowners with airspace property rights up 400 ft, this state law did grant them compensable action against such operations even if the flights did not meet the standards laid out in *Causby*. Such a law is likely in conflict with federal statute as expressed in § 40103(a)(1) and § 41713(b)(1).

However, even if states were granted regulatory control of some low altitude intrastate aircraft or UAS operations, the federal government could still exert control over the state-regulated low altitude airspace through legislative riders that award aviation funding contingent upon state adoption of FAA approved regulations for low altitude operations. This legislative rider process is common and perhaps most notably has been used by the federal government to compel states to set a national legal drinking age minimum at 21 years old by withholding federal highway funding pending compliance (23 U.S.C. § 158).

#### *6.4.1.3 Assignment of Significant Low Altitude Airspace Rights to Landowners*

Regardless of whether regulatory authority for low altitude airspace is ultimately determined to reside with the FAA or the states, landowners were confirmed to have ownership of “the immediate reaches of the enveloping atmosphere” by the Supreme Court ruling in *Causby*. The *Causby* case refrained from setting the altitude limit of private airspace ownership, choosing instead to base it upon disturbance of the “enjoyment and use of the land.” However, with advanced UAS technologies that could arguably hover tens of feet above private property without causing an unreasonable disturbance, the courts or legislatures may consider establishing a fixed height

threshold for private airspace ownership. If this were to occur, then landowners could exclude flights from their private airspace and pursue trespass torts for unlawful entrance into this airspace.

The severity of the potential operational limitations in private, low altitude airspace with respect to UAS or ODM operations is dependent upon the altitude which it extends to. Some authors have argued that private airspace should extend to as high as 500 ft in order to provide sufficient protections [175]. Extending private airspace to such heights would significantly inhibit UAS operations (which are currently limited to 400 ft in maximum altitude by Part 107), and would also place substantial constraints on ODM operations during landing and takeoff.

Private airspace is unlikely to be defined as reaching all the way to 500 ft, however. The Supreme Court confirmed a helicopter flight at 400 ft was conducted in publically accessible airspace (see *Riley*). The author proposes that the ultimate determination of the extent of privately owned airspace is likely to be derived from existing condominium and overhang encroachment law precedents, as discussed in Section 6.5.2.

The assignment of private airspace ownership to a low altitude will place few operational constraints on flight by negating potential trespass claims from landowners. However, landowners could still lodge nuisance and government takings claims against operations well above the private airspace boundary, and perhaps even into navigable airspace, if aircraft operations are sufficiently objectionable. Therefore, low altitude flight above the private airspace altitude boundary should be viewed as acceptable to the public on a continuum where the lesser the *disturbance footprint* of the vehicle, the closer to private airspace threshold the aircraft will be allowed to fly. The disturbance footprint of an aircraft characterizes the noise, light, vibrations, viewshed disturbance, fumes, fuel particles and tactile impacts (such as downwash or dust disturbance) created by the vehicle at a particular instant in flight. Section 6.5.2 discusses this concept of a *continuum of acceptability* in detail.

#### **6.4.2 Potential Limitation on Operations in Historical “Navigable Airspace”**

Even if UAS and ODM operators resolve to operate only within airspace that has historically been used for aviation in the status quo system, the current state of the law potentially provides mechanisms for public pressure to prevent UAS or ODM aircraft from using that airspace. For example, the FAA currently responds to citizen noise complaints for aircraft or helicopter operations at low altitudes by assigning required flyways or routes, limiting airport hours of operation, or excluding some vehicles or operations all together from an area or airport [183].

Outside of FAA action, local jurisdictions or private individuals may also in some cases exclude UAS and ODM operators from specific ground infrastructure. Santa Monica Airport has been under pressure from the Santa Monica City Council and citizens for multiple decades due to the high volume of flights in and out of the airport in close proximity to the public [184]. If ODM Aviation greatly increases flight density to community airports and helipads, resistance to airports may intensify or appear where none previously existed.

As was indicated in Section 6.3, the Supreme Court ruling in *Griggs v. Allegheny County* indicates that it may be possible for landowners to successfully argue a government taking occurred even if aircraft are operated according to all federal regulations and in navigable airspace. *Griggs* may

therefore suggest that ODM aircraft or UAS operating in historical low altitude airways are not automatically protected.

For example, one author has suggested (ambitiously) that ODM aircraft could takeoff every 10 seconds from the same runway in the same direction during high density operations [59], [60]. Disregarding the technical feasibility of this, if flights were to occur at such densities then a case could potentially be successfully pursued that argued a new takings occurred, or a nuisance had been created due to the noise, lights, or mere viewshed impairment from so frequent of operations, even though these operations were in the navigable airspace approach and departure paths which are considered navigable airspace.

As a final example of this potential threat to low altitude aviation, consider the deployment of high-precision arrival and departure procedures (RNAV procedures) at many major airports. Implemented RNAV-1 procedures require aircraft to use satellite navigation or other precision flight equipment to fly within one nautical mile of the specific trajectory [185]. The conventional procedures for these airports, on the other hand, routed aircraft through the use of radio navigation beacons, headings and ATC prescribed vectors. The combined precision of these conventional methods was relatively low and resulted in the dispersion of aircraft operations over a relatively large area around the specified trajectory compared to the RNAV procedures.

The result of the implementation of RNAV procedures has been to concentrate commercial flights along a few precision trajectories. The concentration of flights substantially increased the frequency of which *some* landowners' properties are overflown compared to the previous procedures which distributed the impacts of overflight over a broader area. The concentration of noise, in particular, has in some cases led to public resistance to the adoption of the new ATM technology and even led to attempted congressional and legal action to prohibit the implementation of the new routes [186], [187].

Considering this situation in light of ODM Aviation or UAS, while current private and commercial operators may have the legal right for flight in navigable airspace, there is the potential that this right would not hold for UAS or ODM Aviation operations if they occur at significantly higher density than current operations.

## ***6.5 Potential Approaches to Resolve Policy and Legal Uncertainties***

Novel aviation technologies are emerging that provide fundamentally new capabilities for flight, communications and ground interaction. These technologies have brought to the forefront the policy and legal uncertainties identified in this thesis. While the absence of clear airspace ownership and a low altitude airspace regulatory authority has largely been viewed as a negative occurrence for the aviation industry, it does have the upside of providing legislators, regulators, courts and the industry with a great degree of flexibility to implement an equitable, safe and efficient approach for the allocation and use of low altitude airspace. This section will discuss a few potential approaches to resolve these uncertainties in such a balanced way.

### **6.5.1 Airspace Regulation**

The question of *who* regulates low altitude airspace is an important one, but perhaps not as important as the question of *how* the airspace will be regulated. Section 6.3.1 presented a variety of information addressing the question of who (either local municipalities or the FAA) has the



authority to regulate low altitude airspace. It is the opinion of the author that the FAA is best suited to fulfill this role and balance the desires of the flying public with the rights and safety of the non-flying public. Congress has clearly stated its intention for all airspace to be under FAA control, however this uncertainty revolves around the legal basis of the federal government to apply the Commerce Clause to operations in these airspaces. Therefore, the responsibility must fall to the U.S. courts to close this uncertainty. Among other methods, the courts could do this in favor of the FAA through an interpretation of 49 U.S.C. § 44701 or § 40103(b)(2) by holding the FAA must regulate low altitude airspace to provide for the safety of the aircraft involved in interstate commerce, and is necessary for the FAA to ensure the safety of people and property on the ground.

Moving beyond the *who*, the remainder of this sub-section will focus on the question of *how* low altitude airspace should be regulated, agnostic of the ultimate regulator. First of all, the FAA has expressed concern that a “patchwork quilt” of local municipality regulations could erode safety and increase the complexity of aviation operations. This suggests that regulations must be consistent between municipalities within a relatively large geographic region (such as a state or megaregion) to limit such negative consequences. This could be accomplished either through a single set of national FAA standards, or through complementary standards between adjacent municipalities or states.

Second, any implemented low altitude airspace regulation should recognize and embrace the changes that developing technologies will have on the flight capabilities of future vehicles. As one commentator has explained, “it is important to recognize the near impossibility of predicting all the ways that a rapidly developing technology can be used, for good or for ill, in future years” [180, p. 517]. Considering this, operational regulations may be written with built-in flexibility to handle advancements in technology. The current FAA regulation for minimum separation criteria is a prime example of this in action. §91.111 states that “no person may operate an aircraft so close to another aircraft as to create a collision hazard.” This regulation (though often assailed as overly vague) may enable UAS and aircraft to operate in increasingly closer proximity to one another as vehicle to vehicle communication technologies facilitate such operations.

Alternatively, if the flexibility gains of regulations written in this way are outweighed by the confusion and costs of their vagueness, the regulatory authority may consider adopting a “planned adaptation” process. Planned adaptation involves drafting and implementing regulations with the express intent to gather operational feedback and revisit the regulations after a specific period of time in order to consider necessary updates. Such an approach has been shown to provide better matching of the pace of regulatory development with technology (or knowledge) advancement [108].

Third, low altitude airspace regulation must be implemented along with an enhanced expectation of pilot mindfulness and community responsibility. Creating a set of regulations that would ensure aviation activities are always courteous to people below would be burdensome and overly rigid. Instead, regulations should cover the major operating aspects needed for safety of efficiency, while pilots should be educated and adhere to additional voluntary measures that help avoid public ire and limit privacy/nuisance complaints. The HAI *Fly Neighborly Guide* is a fine example of such voluntary measures that may reduce community impact of low altitude helicopter flight.

Finally, if the FAA were to extend navigable airspace all the way to the surface of the earth (or define a new type of UAS/ODM/helicopter low altitude navigable airspace) as new vehicles appear with increasingly lower minimum safety emergency landing altitudes, it will be necessary for the FAA to enact a variety of regulatory changes in response. For example, 49 U.S.C. § 44718 requires that all structures that may interfere with air commerce (by entering the navigable airspace) must be announced publically and may be subject to an impact study before their construction, alteration or removal. Therefore, if navigable airspace were extended to the ground, this code would become unreasonable as it would require the instillation of even a back yard clothesline to apply for approval or an exemption from the FAA. This regulation, as well as others, would necessarily need to be reconsidered if the FAA sought to expand airspace regulation to the ground.

## **6.5.2 Airspace Ownership and Protection of Landowner Rights**

Arguably the most pressing legal question discussed in this thesis is if ownership of airspace above private property exists, and to what altitude such ownership may extend. Through *Causby* and the proceeding cases, the Supreme Court definitively answered that private ownership of low altitude airspace is a given right of property ownership. Furthermore, the case also gave the guidance that a property owner has exclusive rights to as much airspace as they can reasonably require for the enjoyment or use of their land. Finally, the Supreme Court found that landowners may still be protected from unreasonable aircraft operations outside of their private airspace, even if these operations occurred in what is considered FAA controlled navigable airspace.

Considering these findings from the Supreme Court, the key limitation for UAS operations is likely to be the demarcation altitude for private airspace, while the key limitation for ODM Aviation operations is more likely to be the protection of landowners from nuisance resulting from operation of these larger vehicles. The distinction here is due to the fact that the small footprint of UAS will enable them to operate at much lower altitudes without causing disruptions legal qualifying as a nuisance. UAS are therefore more likely be restricted from low altitude flight by trespass into private airspace, particularly if private airspace is defined to reach to multiple hundreds of feet above the ground. The greater footprint of ODM aircraft (due to their increased size) will likely prevent these vehicles from operating near the demarcation altitude of private airspace as these vehicle would trip nuisance claims at higher altitudes.

### *6.5.2.1 Private Airspace Ownership Demarcation Altitude*

Considering these factors, it is possible to hypothesize a range of altitudes private airspace is likely to extend to based upon the analysis presented in Section 6.3. From *Causby*, the Supreme Court found that the flight of loud, jet aircraft at 83 ft above private, rural property was a takings by the government and constituted an appropriation of the use of the land below. However, this case did not contribute directly to a definition of private airspace as it established government takings is awarded based upon an appropriation of the use of the land below, rather than an appropriation of the private airspace itself. This means that 83 feet is not definitively inside private airspace, even though the flight of jet aircraft at this altitude was a violation of property rights by the government.

Rather than government takings, the best guidance for private airspace definition comes from privacy cases as summarized in Table 39. From *Riley*, the Supreme Court found that the flight of a helicopter at 400 ft above private, rural land occurred in public airways and was not considered an appropriation of the use of the land below. This almost certainly suggests that private airspace

ownership does not de facto extend up to 400 ft. It may be the case, or course, that if the landowner has a legitimate use of the land above 400 ft (such as through the construction of a wind turbine), then their private airspace would extend up to that height. In a sense, it can be imagined that the construction of structures of height reallocate public airspace to the landowner, and the destruction of such structures restores private airspace to the public domain.

*Riley* therefore may be interpreted to set the maximum potential reaches of private airspace to 400 ft, but gives no further clarification to the actual demarcation altitude. Beyond this federal case law, the best barometer for what this demarcation altitude is resides in common and state laws concerning overhang encroachment and condominium laws.

Condominium laws enable individuals to buy volumes of land in the air above their property and litigate against trespass into these volumes with the same strict liability rules that apply on the surface [175]. Similarly, as the author of this thesis rudely discovered with respect to his Bradford Pear trees, common law protections from overhang encroachments give property owners the right to force the removal of overhanging objects from the airspace above their property at their neighbor's expense.

Each of these two legal pathways are currently accepted in the status quo system and directly imply (or explicitly state in the case of condominium rights) the private ownership of airspace. Furthermore, each of these laws suggests airspace ownership in a manner that is consistent with the *Causby* language “the landowner owns at least as much of the space above the ground as he can occupy or use in connection with the land.” Taken together, these laws would almost certainly provide landowners with ownership of airspace up to the height of the tallest tree in rural areas, and up to the maximum building height ordinance (if one exists) in congested areas.

The adoption of a hard-line demarcation altitude for de facto private airspace ownership by the legal system, FAA and industry may be beneficial for the UAS and ODM Aviation industries as it would create clear property rights and expectations of privacy. This could ultimately avoid unnecessary trespass and privacy litigation. However, there is a threat to low altitude operations that this demarcation altitude could be set at high as 400 ft which would be detrimental to UAS operations and to ODM Aviation operations to a lesser degree.

#### 6.5.2.2 A “Continuum of Acceptability” for Low Altitude Aircraft Operations

A private airspace altitude demarcation would provide a hard-line boundary below which no aircraft could fly, except through permission from the landowners, without being subject to trespass tort action. Such a threshold would also protect aircraft flying above the demarcation altitude (in public airspace) from trespass or privacy litigation for naked-eye observations. However, flight above this demarcation *does not* automatically protect aircraft operators from litigation concerning nuisance, government takings, or surveillance/privacy invasion with advanced imaging devices.

Above the private airspace demarcation, the balance of landowner rights with pilot rights may be imagined as a “continuum of acceptability.” The landowner's right to “use and enjoyment” of their land enables them to make nuisance or government takings claims well above their property, and perhaps even into the navigable airspace above the fixed-wing operating minimum altitudes if

aircraft operations are sufficiently objectionable. However, the higher the altitude at which the operation occurs at, the more objectionable (louder, brighter, more frequent, etc) the operation must be. This concept is well expressed in *Stephens v. United States*:

*As the height of the overflight increases... the Government's interest in maintaining air sovereignty becomes weightier while the landowner's interest diminishes, so that the damage showing required increases in a continuum toward showing absolute destruction of all uses of the property.*

Under a “continuum of acceptability” paradigm for low altitude flights, vehicles with small disturbance footprints, such as a small UAS that creates little noise, light or vibrations, would likely be able to operate close to the private airspace demarcation without tripping nuisance or takings litigation. Vehicles with slightly larger disturbance footprints, such as electric ODM aircraft, may need to operate well above this boundary except during landing or takeoff in order to prevent legal action by landowners. Loud aircraft, such as jet aircraft, may need to operate at the top of the continuum at much higher altitudes in order to avoid undue infringement of property owners’ rights. Establishing acceptable operating altitudes for various vehicles will likely be the result of significant scientific research, public debate and legal action.

#### 6.5.2.3 *Avigation Easements as a Mechanism to Protect the Rights of Landowners and Aircraft Operators*

The FAA has already developed a legal mechanism through *avigation easements* to protect the rights of landowners and provide protections for aircraft operators. Avigation easements typically exist in the vicinity of airports where landing and takeoff operations require aircraft to operate below an acceptable altitude for their disturbance footprint, and perhaps even pass through the private airspace of nearby landowners. Avigation easements have been acquired by airports in Los Angeles and around the country through various means including eminent domain, as a condition for the approval of property development, as a condition to install soundproofing, or through “prescription” in some states where years of uncontested flights over private property automatically grant the airport the easement [188]–[190].

Avigation easements are volumes of airspace over neighboring properties that airports acquire in order to protect the safe operation of aircraft to and from the airport. As stated in a FAA template for avigation easements, landowners accept the following terms through the easement [191]:

1. “The unobstructed use and passage of all types of aircraft in and through the airspace at any height or altitude above the surface of the land.”
2. “The right of said aircraft to cause noise, vibrations, fumes, deposits of dust, fuel particles... fear, interference with sleep or communication, and any other effects associated with the normal operation of aircraft taking off, landing or operating in the vicinity of [the airport].”
3. “The Grantors agree...they will not construct, erect, suffer to permit or allow any structure or trees on the surface of the burdened property”

Avigation easements provide airports with a mechanism to insure nearby landowners do not improve their land in a way that imperils the safe operation of aircraft into or out of the airport.

Secondly, the easements protect the airports and pilots against liability from tort action (trespass, nuisance, invasion of privacy, etc) caused by the use of the airspace. Furthermore, while many airports have not directly secured aviation easements over the adjacent private properties, they may often claim the easement exists by “prescription” due to the historical uncontested operation of aircraft over the land [169]. In either case, aviation easements provide a mechanism that aircraft operations of any type, altitude, flight density and time may be legally protected from airspace ownership questions or nuisance torts.

Aviation easements therefore represent a mechanism that provides fair compensation for landowners and protections for aircraft operators and airports in areas where aircraft are frequently landing and taking off from. As UAS or ODM Aviation takeoff and landing areas become more common and congested in communities, aviation easements may become more frequently used.

### **6.5.3 Airspace Design and Air Traffic Management**

Changes in controlled airspace (Class A – E) design, such as those executed at the nation’s largest airports through the FAA Metroplex initiative, require millions of dollars of investment and years of process. Considering this, it is likely that UAS and ODM Aviation will operate within the status quo airspace definitions.

Except for in the areas immediately around airports, a majority of airspace below a 1200 ft AGL is uncontrolled Class G airspace (see Figure 66). Within this low altitude Class G airspace there may be an opportunity to conduct new airspace design or air traffic management (ATM) to support the efficient and safe flight of vehicles in these areas, as well as protect the rights of landowners and bystanders on the ground. As changes in low altitude airspace design are likely to become codified in regulation (and therefore gain a high inertia challenging change in the future), care should be taken in the near term to adopt a system that will have the flexibility to grow and adapt to the needs of both UAS and ODM aircraft operations.

Figure 69 displays one such ATM proposal by Amazon that segregates small UAS operations below 500 ft by vehicle capabilities and creates “no-fly zones” in controlled surface-level airspaces around airports. Similarly, Figure 70 displays an alternative proposal by Google to implement a more traditional ATC style system in Class G airspace below 500 ft where a private or public company acts as an airspace service provider and “performs UAS traffic planning, airspace supervision and separation assurance using existing cellular networks” [192].

[Intentionally left blank]

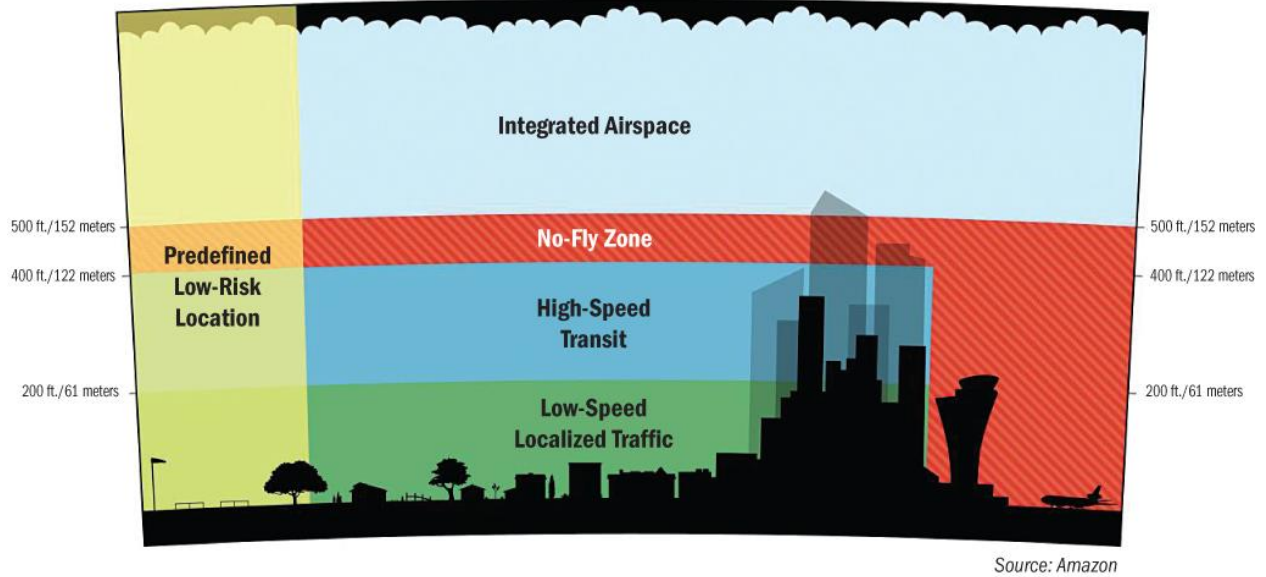


Figure 69. Amazon airspace design proposal for small UAS operations below 500 ft showing a segregated operation airspace scheme for manned vehicles and UAS where UAS are separated by speed capability. Image retrieved from [192].

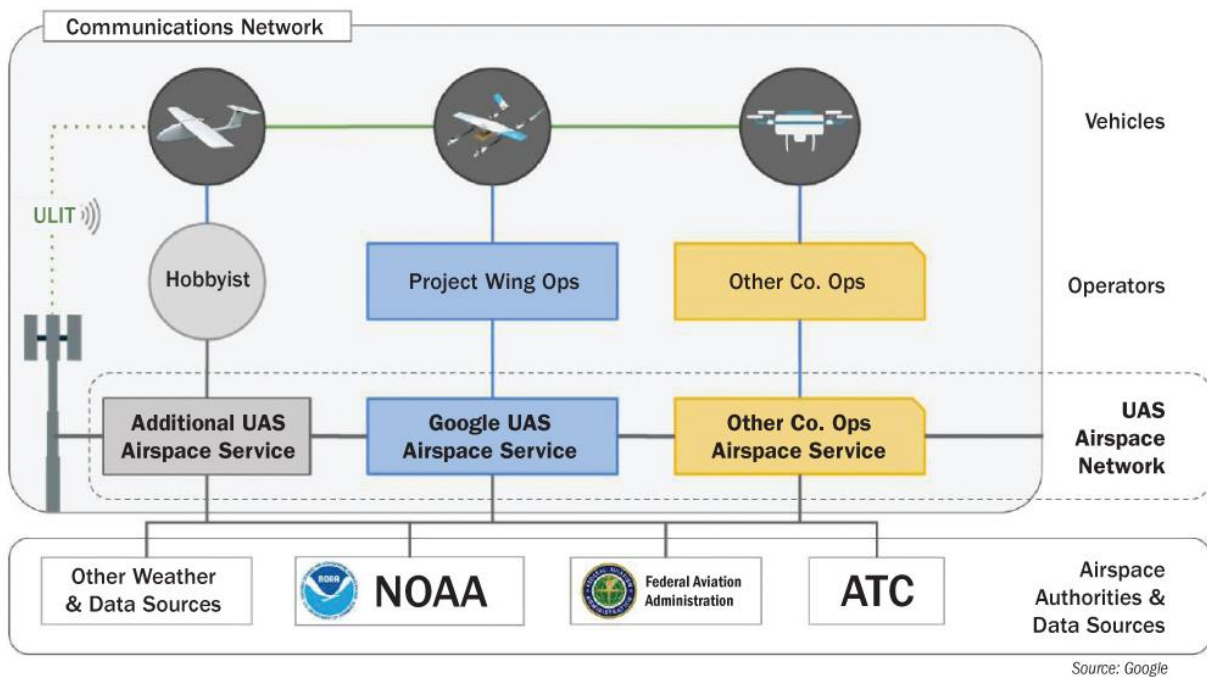


Figure 70. Google airspace design proposal for small UAS operations below 500 ft where various “airspace service providers” offer ATC services for vehicles and enable mixed operations of UAS and manned aircraft in the same airspace. Image retrieved from [192].

While significant research must be done to identify how to optimally manage air traffic at these low altitudes and design airspaces to support efficient and safe operations, in general it appears that a segregated airspace scheme such as the one proposed by Amazon could be more restrictive to future operations, particularly ODM Aviation operations. Creating an airspace system that designates particular altitude bands for UAS-only flight may require future ODM operators to request special permission to access such airspaces, and potentially give them lower priority than established UAS operators when landing outside the “no-fly zone” airports. Alternatively, a system such as that proposed by Google may allow ODM and UAS to operate simultaneously in the same airspace with negotiated priority allocation.

Modifications to either proposed scheme, as well as other low altitude airspace design schemes not included in this thesis, may all lead to an acceptable system for both manned and unmanned aviation. Care should be taken now to adopt a system that will have the flexibility to grow and adapt to not just UAS operations, but also ODM Aviation operations in the future.

## **6.6 Summary**

Current airspace definitions, aircraft operating regulations and case law have left significant grey areas, or areas of uncertainty, concerning the extent to which:

1. A landowner has property rights to the airspace above the surface of their land,
2. How a landowner’s rights are balanced with the rights of pilots flying above their property,
3. If the federal or local governments have the authority to regulate aircraft operations below the historically defined navigable airspace limits.

The review presented in this chapter provided an overview of the laws, regulations and cases addressing these questions, and the potential impact they may have on low altitude UAS and ODM Aviation operations. Finally, a variety of potential approaches to resolve the uncertainty were addressed.

It is the stated position of the FAA that they have the sole right to regulate aircraft operations all the way to the surface and that privacy and nuisance laws provide local municipalities with appropriate mechanisms to protect their citizens from unreasonable low altitude flight. The review of this chapter indicated that the FAA does indeed have a reasonable claim to such powers. However, in addition to local municipality privacy and nuisance laws, the Supreme Court has clearly stated that landowners have ownership rights to some volume of airspace immediately above their property. Therefore, landowners also have the right to exclude or limit flight within this “private” airspace through trespass and privacy tort action. The extent to which the private airspace extends to is uncertain at this time.

Table 40 displays the proposed ownership and regulatory rights of airspace as determined by the study conducted in this thesis. The remaining areas of legal and regulatory uncertainty reside in the extent of private airspace ownership by landowners, and what entity has regulative authority below navigable airspace. While the Supreme Court had found that helicopter operation above 400 ft is in public airspace, no fixed-height demarcation altitude for private airspace has been set. Based upon the Second Restatement of Torts, airspace within 50 ft of the surface is frequently considered private. However, the exact extent of private airspace remains an area of significant uncertainty.

Table 40. Airspace ownership and regulatory authority as derived from current statutes and regulations with potential low altitude airspace ownership demarcation altitudes.

| <b>People/<br/>Property<br/>Beneath</b> | <b>Navigable<br/>Airspace<br/>Boundary<br/>(NAB)</b> | <b>Airspace<br/>Ownership<br/>Below<br/>NAB</b>   | <b>Airspace<br/>Ownership<br/>Above<br/>NAB</b> | <b>Airspace<br/>Regulation<br/>Below<br/>NAB</b> | <b>Airspace<br/>Regulation<br/>Above<br/>NAB</b> |
|---|--|---|---|--|--|
| Open water/sparsely populated land      | Min. emergency safe landing alt.                     | <50 ft, likely private*<br>>50 ft & <400 ft<br>Unknown*<br>>400 ft, almost certainly commons* | commons   | FAA/State?                                       | FAA  |
| Non-congested areas                     | 500 ft   |   | commons   | FAA/State?                                       | FAA  |
| Congested areas                         | 1000 ft  |   | commons   | FAA/State?                                       | FAA  |
| Takeoff & Landing                       | SFC to 1000 ft                                       | Commons via avigation easement  | commons   | FAA  | FAA  |

\*if landowners are actively using the airspace, perhaps through a built structure such as a telecommunications towers, then high altitude airspace around this structure may be considered privately owned rather than in the public commons.

Perhaps the most significant finding of this chapter is that while the private airspace demarcation altitude is paramount in determining where aircraft may and may not operate from a trespass standpoint, above this altitude there exists a *continuum of acceptability* where flights may still trigger nuisance or government takings litigation due to their *disturbance footprint* (which characterizes their noise, light, vibrations, viewshed disturbance, fumes, fuel particles and tactile impacts). This implies smaller, less impactful vehicles may be able to operate at the private airspace demarcation threshold altitude while larger, high impact vehicles will be relegated to greater altitudes except during takeoff and landing.

Figure 71 displays an impression of the regulatory considerations for low altitude airspace operations. Airspace ownership is private below the “private airspace demarcation” line, and is a public commons above. Around airports or congested TOLAs, private airspace has been acquired for frequent aviation use through avigation easements. Aircraft flights in private airspace are trespassing unless given permission by the landowner. Neighbors may still file nuisance claims against such permissible private airspace operations and may have a compensable case if the operations are frequent and damaging enough to be sufficiently objectionable in the eye of the courts.

Above the private airspace demarcation line aircraft may legally operate if they meet the specific minimum safe operating altitude requirement set for that vehicle type by the FAA. However, all operations are subject to the *continuum of acceptability*. Therefore, although flying legally, an aircraft may still be subject to nuisance or government takings lawsuits if its disturbance footprint is sufficiently objectionable to landowners and diminishes the use and enjoyment of their land.



Finally, where landowners have established use of an airspace, such as through the construction of a building over and above the standard private airspace demarcation altitude, they have effectively extended their private airspace upwards. It is unclear at this time how far laterally private airspace will extend from structures such as high-rise apartments, and this will likely be a subject of legal debate for UAS operations in proximity to skyscrapers and other structures.

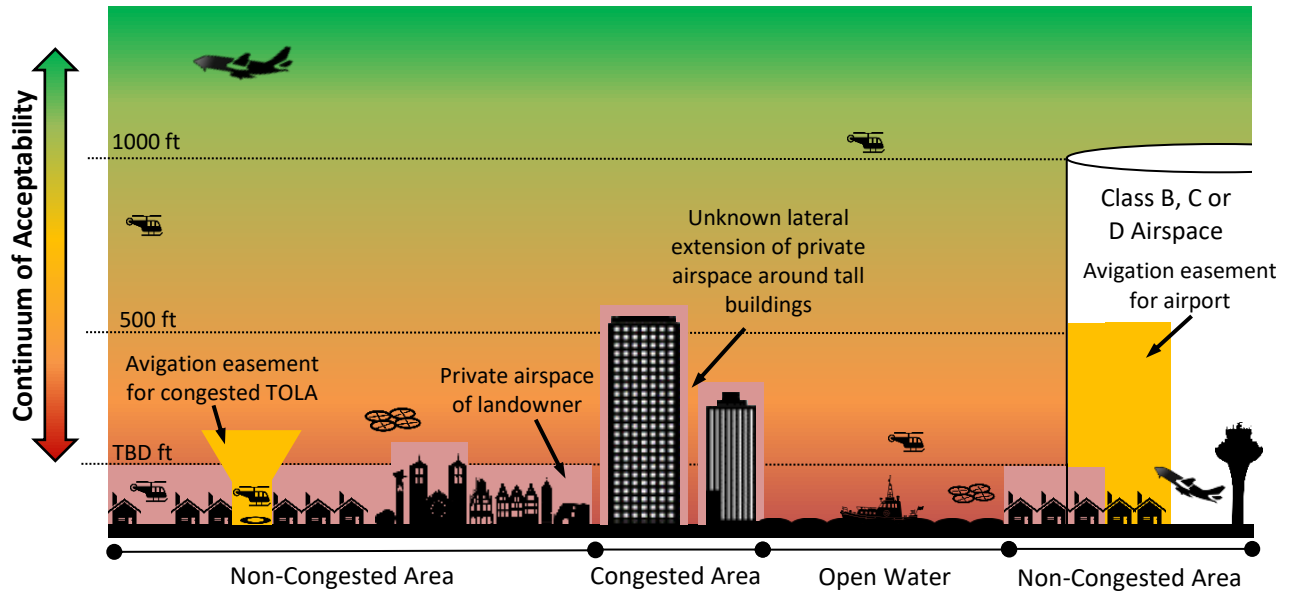


Figure 71. Notional diagram for low altitude airspace operations displaying private airspace owned by landowners where flights cannot proceed with permission, the use of avigation easements by airports or contested TOLAs to protect landing and departure routes, and the continuum of acceptability above the surface where vehicles with a smaller disturbance footprint may fly lower without triggering nuisance or government takings litigation by ground residents.



## 7 Review of Operational Constraint Mitigation Approaches

Chapter 5 identified 20 operational challenges that ODM Aviation networks may face. These 20 challenges vary dramatically in the severity of impact they may have upon the operation of ODM services. For example, insufficient customer access to a rooftop TOLA may only be an inconvenience, while not receiving ATC clearance to enter a controlled airspace is a more “binding” constraint. Furthermore, the severity of any particular challenge was hypothesized to be dependent upon factors such as the number of ODM operations (network scale), the geographic location of the operations, the time of day they occurred, and the weather conditions, among others. The 20 operational challenges were condensed into five *constraints* and three *issues*. Figure 64 displayed a notional concept for how constraint severity may be dependent upon ODM network scale.

In addition to representing varying levels of severity, the operational challenges also differ in the difficulty or expense with which they may potentially be mitigated. Revisiting the two examples given above, customer access to TOLAs may be as simple to mitigate as hiring an escort or installing a new, dedicated TOLA entrance. Assuring ODM aircraft have access to controlled airspaces, on the other hand, could involve non-trivial changes to ATC procedures, staffing, technologies or even regulations. While the ODM Aviation community has proposed a variety of mitigation approaches to address some of the constraints identified through this research, a comprehensive review of the feasibility of these mitigation approaches and their impact on the entire ODM Aviation network has not been conducted.

This chapter reviews how the implementation of these mitigation approaches, as well as others investigated by the author, may potentially address the constraints and issues identified for ODM Aviation. The near-term implementability of each mitigation proposal was first evaluated for a small-scale ODM Aviation network in the near-term. The influence of the mitigation approach on the network was assessed, and the degree to which it may lessen or remove the constraint was considered. Furthermore, ancillary effects of the mitigation approach on other constraints (perhaps beneficial or detrimental) were investigated. Finally, the capacity of the mitigation technique to scale with increasingly dense ODM networks and operations (a far-term consideration) was investigated. Figure 72 presents the general operational potential analysis approach developed in this thesis and outlines the current step of the approach in red. This chapter presents the final investigation of potential mitigation techniques for the identified operational challenges, or the last step of the analysis approach. This investigation drew upon the analyses conducted with respect to the eight different evaluation lenses in Chapters 5 and 6.

The research presented in this chapter may be considered the initial phase of developing a system architecting plan for ODM Aviation. The analysis identified the most prevalent near-term constraints and explored if proposed mitigation approaches were sufficient to support the implementation of early adopter ODM Aviation services. The analysis then continued with far-term planning by investigating approaches to mitigate the constraints that become binding as an ODM network grew in scale. Ideally, the ODM community would be able to use a mature system architecting plan to direct investments to develop technologies and mitigation approaches. Such a plan could minimize investments in constraints that are not currently binding on operations while directing strategic, proactive investments to resolve constraints that may otherwise become severe in the far-term.

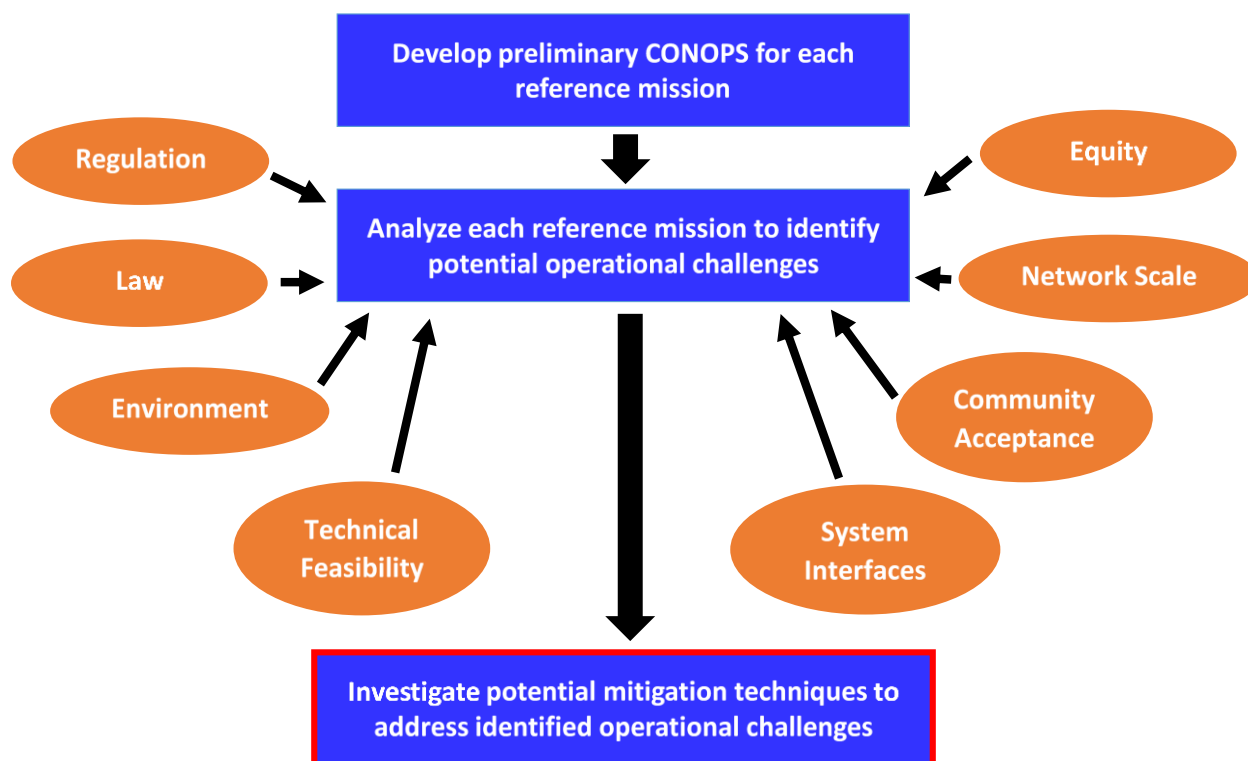


Figure 72. This chapter presents the investigation of potential mitigation techniques for the identified operational challenges, the final step of the analysis approach.

### ***7.1 Availability of Takeoff and Landing Areas***

In order for a public or commercial transportation mode to become competitive with private transportation, the service must provide customers with sufficient geographic coverage of a region to enable relatively easy access to a core set of desired destinations. As Table 13 indicated, automobiles currently enjoy a high geographic coverage that provides customers with door to door service between nearly any two locations. Current public transportation modes, such as buses or subways, typically operate as a lattice network that crisscrosses a metropolitan region providing reasonable geographic coverage to specific corridors and communities. Current aircraft and helicopter operations, however, typically have a very low geographic coverage as they primarily operate from a limited set of ground infrastructure nodes (airports or helipads).

A limited set of mobility nodes (TOLAs, for example) located in key areas of demand may be sufficient to support a sustainable transportation network, albeit with limited growth potential. The heliports in Manhattan are a prime example of such a network. Three high capacity heliports, all located on the waterfront, support a network of helicopter operators ferrying individuals to and from New York’s three major airports; these heliports also support a large tourism industry. If the goal of ODM Aviation is not to just serve a few high-demand routes or corridors, but rather to become a ubiquitous form of transportation, then a network of geographically well-distributed TOLAs is essential. Although not quantitatively assessed in this analysis, it was hypothesized that there is some threshold density of TOLAs in a region that triggers a dramatic increase in consumer demand for the use of an ODM Aviation network.

### 7.1.1 Existing Aviation Ground Infrastructure

Los Angeles was selected as the focus of the initial ODM Aviation case study due in part to the large number of airports and helipads that already exist in the region. The FAA reported in 2013 that Los Angeles County alone had 27 airports and 138 registered heliports, with numerous unregistered emergency helicopter landing facilities spread throughout the region [30]. With this level of built infrastructure, Los Angeles has more improved TOLAs than any city in the United States, and perhaps any city in the world. Yet, despite this marked benefit, the review of the reference missions in Chapter 5 still concluded the geographic coverage of TOLAs in L.A. was insufficient to support wide-spread ODM Aviation operations.

To better identify the current availability of TOLAs in Los Angeles, a study was conducted to identify all of the airports and helipads in L.A. including both registered and unregistered facilities. First, the FAA charts, Helicopter Association International heliport directory and AirNav.com databases were interrogated to collect the location and type (private, public, EMS heliport or airport) of TOLAs included in these resources. Second, a visual scan was conducted of the L.A. basin in Google Earth to identify existing aviation ground infrastructure. The review identified a total of 310 existing helipad or airport facilities within roughly 37 nmi of the Los Angeles International Airport. Table 41 displays the breakdown of these TOLAs by type.

Interestingly, while the L.A. basin hosts an exceptional number of existing TOLAs, 70% of the aviation ground infrastructure are Emergency Helicopter Landing Facilities (EHLFs). An EHLF is a helipad that is not certified by the FAA and is only intended for use for emergency purposes. The design of an EHLF is dictated by local ordinance and may vary from municipality to municipality. Los Angeles County has such a large number of EHLFs because §57.4705.4 of the local municipality code required any building of 75 feet or greater built after 1974 to have either a FAA certified helipad or an EHLF on the roof [193]. While the L.A. Fire Department Requirement Number 10 was updated in 2014 to no longer require a high-rise rooftop helipad [194], the built infrastructure will remain within the county for decades to come.

Table 41. Existing aviation ground infrastructure in the Los Angeles basin.

| Type of TOLA                                 | Number Identified |
|--|-------------------|
| Airport                                      | 16                |
| Police/Government Helipad                    | 15                |
| Medical Services Helipad                     | 24                |
| Private Helipad                              | 37                |
| Public Helipad                               | 0                 |
| Emergency Helicopter Landing Facility (EHLF) | 218               |
| <b>TOTAL:</b>                                | <b>310</b>        |

Figure 73 displays the geographic location of all 310 TOLAs in the Los Angeles basin where the color of the “pin” marker indicates the type of facility. As may be seen in the figure, while L.A. has a significant number of helipads, they are not geographically well-distributed and tend to be aggregated in the central business districts (CBDs). This trend is emphasized in Figure 74 which displays the central Los Angeles CBD. It may be seen that downtown L.A. contains over 80 helipads within a two mile radius, but then hosts little to no aviation ground infrastructure in the surrounding communities.

While the high density of available TOLAs in the CBDs may provide ODM Aviation networks with excellent ground infrastructure serving these high population regions, the surrounding satellite cities, and especially the suburban regions of Los Angeles, are underserved or not served by existing aviation infrastructure. This indicates that the current distribution of ground infrastructure may support point-to-point flights between city centers, or flights from airports and other isolated origin points into the city centers. However, the poor distribution of TOLAs may stunt the demand for ODM daily commuter services or point-to-point services outside these specific corridors.

The poor distribution of TOLAs (which may generally be considered as leading to low TOLA availability) results in three primary operational challenges for ODM Aviation that may all reduce consumer demand. Table 42 provides a summary of these impacts.

Table 42. Operational challenges for ODM Aviation resulting from low TOLA availability.

| <b>Operational challenge resulting from low TOLA availability</b> | <b>Description</b>   |
|---|--|
| Increased first mile/last mile transportation requirements        | Few TOLAs serving a geographic area increases the ground distance some customers must travel to or from an available facility. This ground transport leg adds time, complexity and expense to the overall mission. |
| Increased ground and air traffic congestion                       | Isolated TOLAs may lead to ground and air congestion at those locations, particularly if aircraft turn-time is slow.   |
| Reduced ODM aircraft staging and deployment capacity              | Distributed staging of aircraft is only possible with a high density of TOLA infrastructure in a geographic area.  |

[Intentionally left blank]



Figure 73. Geographic location and type of existing aviation ground infrastructure in the Los Angeles basin. © 2016 Google. Map Data: SIO, NOAA, U.S. Navy, NGA, GEBCO, NSF, USGS.

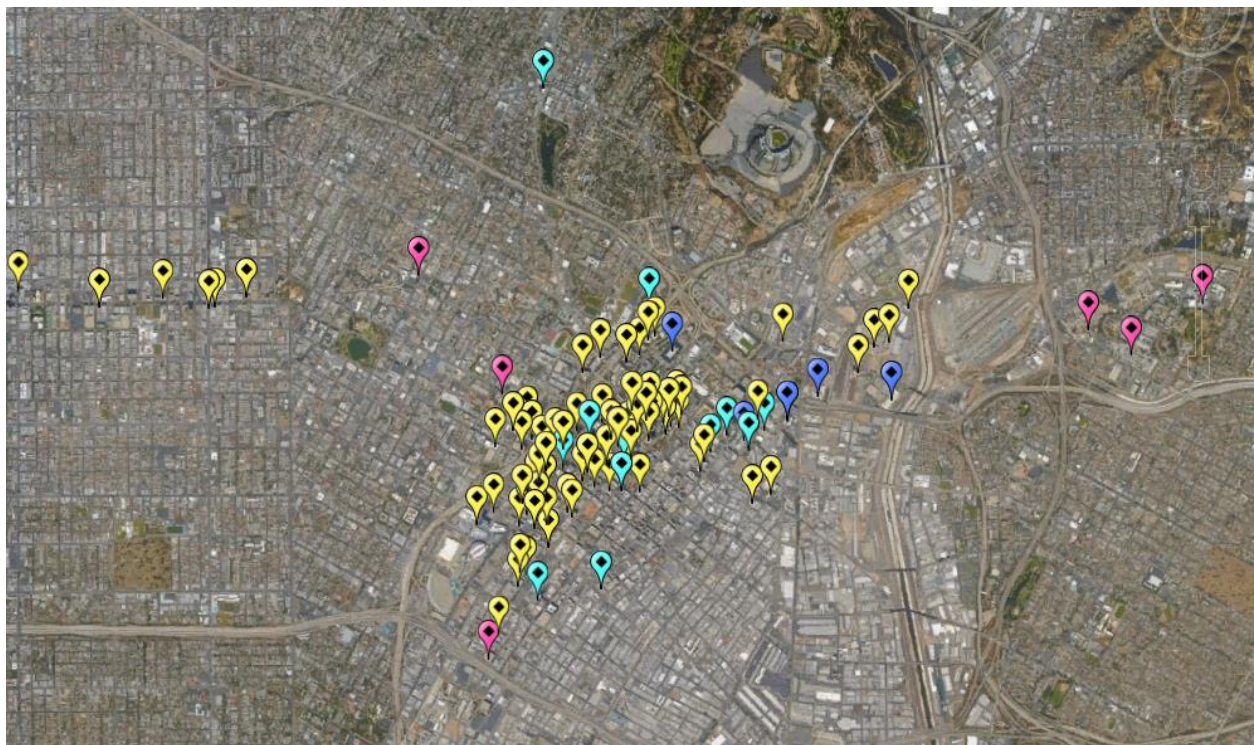


Figure 74. Existing heliport infrastructure quickly drops off outside of the central business districts. © 2016 Google.

### 7.1.2 Approaches to Increase the Availability of ODM Aviation TOLAs

In order for ODM Aviation to serve more than a few specific routes in the Los Angeles basin, the availability of TOLAs must be significantly increased in many underserved areas, and the EHLFs must be certified for commercial operations. There have been a variety of proposals to increase TOLA availability in metropolitan areas, and each proposal impacts the three challenges presented in Table 42 differently. Considering these proposals as a whole, two common approaches emerge:

3. Reduce the landing requirements for ODM aircraft through flexible vehicle designs thereby allowing for ODM operations at smaller, less developed TOLAs.
4. Develop new TOLA infrastructure in high demand potential areas.

Table 43 presents a listing of potential TOLA availability mitigation approaches collected by the author. These concepts were either presented in literature, introduced at the series of NASA ODM workshops, or discussed by the author with stakeholders in the community. Table 43 is not intended to present a complete set of potential mitigation approaches, but rather a sampling of those in consideration by the industry.

Table 43. Potential approaches to increase TOLA availability.

| <b>Reduce TOLA landing requirements through flexible vehicles</b> | <b>Develop new TOLA infrastructure</b>   |
|---|--|
| Lowerable basket, ladder, or gondola                              | TOLAs overtop highways, roads or rails   |
| Tall landing gear to land overtop parked cars                     | TOLAs within highway clover leaf clearings   |
| Diminished downwash to reduce TOLA size                           | TOLAs co-located with gas stations, superstores, or other geographically well-distributed businesses |
| Vehicles certified to land on small footprints                    |  |
| Vehicles with fast surface turn-time operations                   | TOLA development overtop parking lots or on the top floor of multi-level parking decks               |
| Vehicles with reduced noise profiles                              | TOLAs on rooftops  |
| Vehicles capable of landing on a variety of unimproved surfaces   | TOLA development on docks or floating barges   |

Achieving significantly increased TOLA availability in Los Angeles (or any city for that matter) will likely require investments in a portfolio of these potential mitigation approaches, subject to the unique characteristics of the particular area. Developing more flexible ODM aircraft that reduce the disturbance of landing (noise, downwash, etc.) while allowing for the safe maneuvering of the vehicle in smaller areas (deadman’s curve, stability and control, etc.) will be important enablers of developing improved TOLA facilities in communities, or perhaps allowing for off-heliport landings at unimproved TOLAs. Supplementing the existing TOLAs with a diverse network of new TOLA infrastructure may also be necessary to create viable and ubiquitous ODM networks.

In order to assess how the various mitigation approaches for TOLA availability outlined in Table 43 may address this constraint for near-term and far-term ODM networks, an infrastructure development investigation was conducted in a region of Los Angeles currently underserved by TOLAs. Figure 75 outlines the 101 square mile reference area chosen for this study. The reference



area spans from the shoreline just below LAX down to the beginning of the Palos Verdes Peninsula and reaches eastward to Interstate 710. There are currently 10 TOLAs in the reference area including three private heliports, three community airports, three EHLFs and a hospital helipad. The maximum driving distance from within the reference area to reach the closest TOLA is 5.5 miles. This trip may take as much as 35 minutes during peak traffic periods.

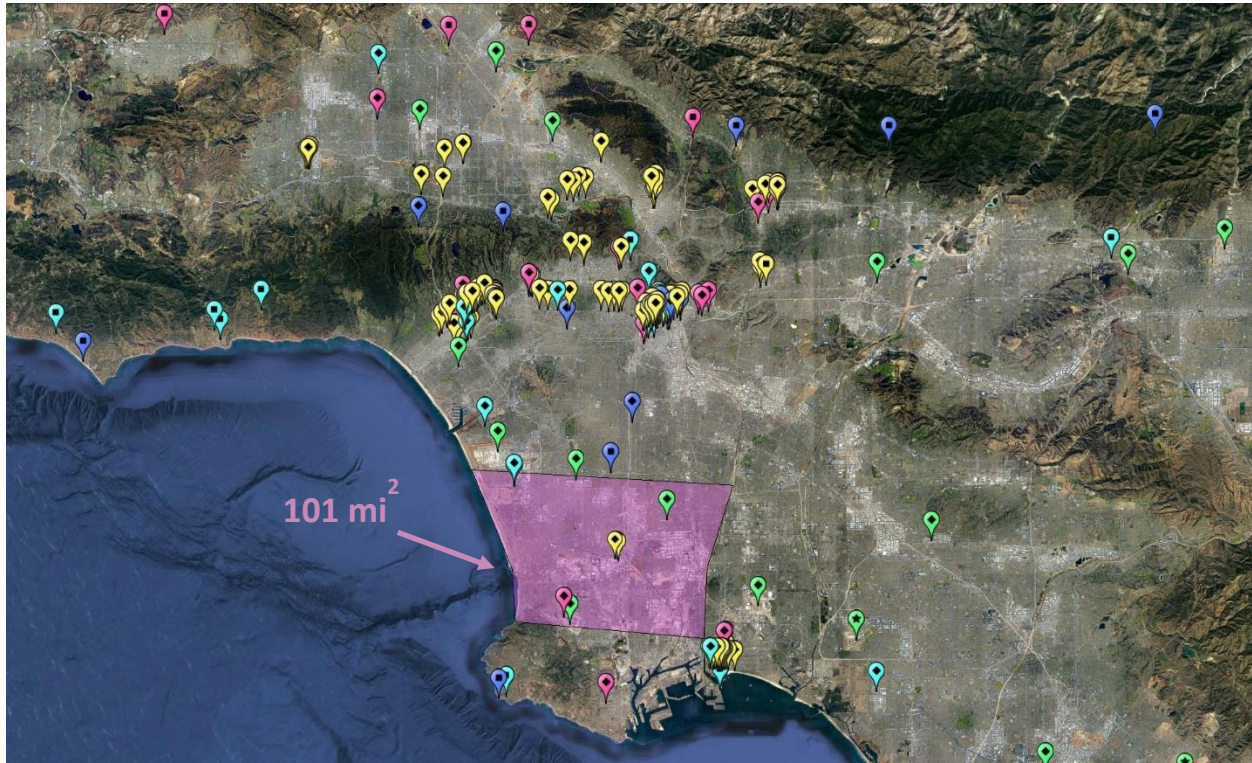


Figure 75. TOLA availability new infrastructure development mitigation investigation reference area. © 2016 Google. Map Data: SIO, NOAA, U.S. Navy, NGA, GEBCO, NSF, USGS.

The first consideration for this investigation was the capacity of new TOLA infrastructure that may be developed. Figure 76 presents two infrastructure options at differing ends of the capacity spectrum. The left image is a small TOLA with a single touch-down and liftoff (TLOF) surface and no additional aircraft parking. Such infrastructure is by far the most common in Los Angeles as all of the EHLFs, private helipads, medical helipads and a majority of the public service helipads are of this type. These single-pad TOLAs, sometime referred to as vertipads or helipads (as opposed to vertiports and heliports), have the advantage of flexibility in their location, requiring little space and being comparatively cheap to construct and maintain. However, single-pad TOLAs are only able to handle one operation at a time and therefore have a low throughput capacity per facility.

The right image of Figure 76 displays the Jay Stephen Hooper Memorial heliport, the primary facility for the L.A. Police helicopter fleet. This heliport is an example of a high-capacity TOLA with two TLOFs and over a dozen aircraft parking slots. Additionally, the facility has the enhanced attributes of onsite ground vehicle parking, an Instrument Landing System (ILS) to support all-weather operations, and on-site services including maintenance, fueling and passenger/staff staging areas. High-capacity TOLAs therefore address challenges such as TLOF congestion,

vehicle staging, customer access, safety and security, and ground vehicle parking. However, these facilities are significantly more expensive than single-pad TOLAs, required substantial dedicated land-use (or large rooftops such as parking garages), and concentrate aviation operations (and their impacts such as noise) in a single geographic area.



*Single-Pad TOLA*



*High-Capacity TOLA*

Figure 76. Potential TOLA infrastructure options with dramatically differing throughput, staging, services, customer access and cost attributes. © 2016 Google.

Considering the characteristics of single-pad and high-capacity TOLA infrastructure, it was determined that high-capacity TOLAs are appropriate to be constructed in areas of high consumer demand and anticipated network throughput, such as in CBDs, at airports, at event venues, or at intermodal transportation hubs such as train or bus stations. The reference area of the infrastructure investigation did not have any such areas that were predicted to concentrate demand, and therefore only the development of new single-pad TOLAs was examined.

A majority of the new TOLA infrastructure options proposed in the right hand column of Table 43 could theoretically be implemented in the reference area. As proposed in a Georgia Tech study on UAS package delivery, the co-location of new aviation ground infrastructure with existing, geographically well-distributed businesses such as gas stations or convenience stores is an attractive pathway to support early adopter markets [95]. Developing new TOLAs with these business entities could be completed en masse through a single contractual agreement, be covered

by a single insurance policy, and potentially provide strong incentives for mutually beneficial partnerships. Considering these potential benefits, this particular mitigation approach was initially chosen for review.

Figure 77 displays the geographic distribution of TOLAs in the reference area if a facility were co-located with existing gas stations. In the 101 square mile reference area 116 gas stations were identified. The locations of the gas stations were relatively well-distributed in the reference area and reduced the maximum driving distance from any point to a TOLA to 1.7 miles. Furthermore, some major roadway intersections hosted up to three gas stations suggesting that these areas could function at higher capacity with coordinated operations between the TOLAs. It should be noted that TOLA construction and approval challenges (including local zoning and FAA approvals) were not considered in this initial mitigation proposal review. Section 7.1.3 investigates how regulatory, community acceptance and operational factors may restrict the development of a TOLA at any particular location.

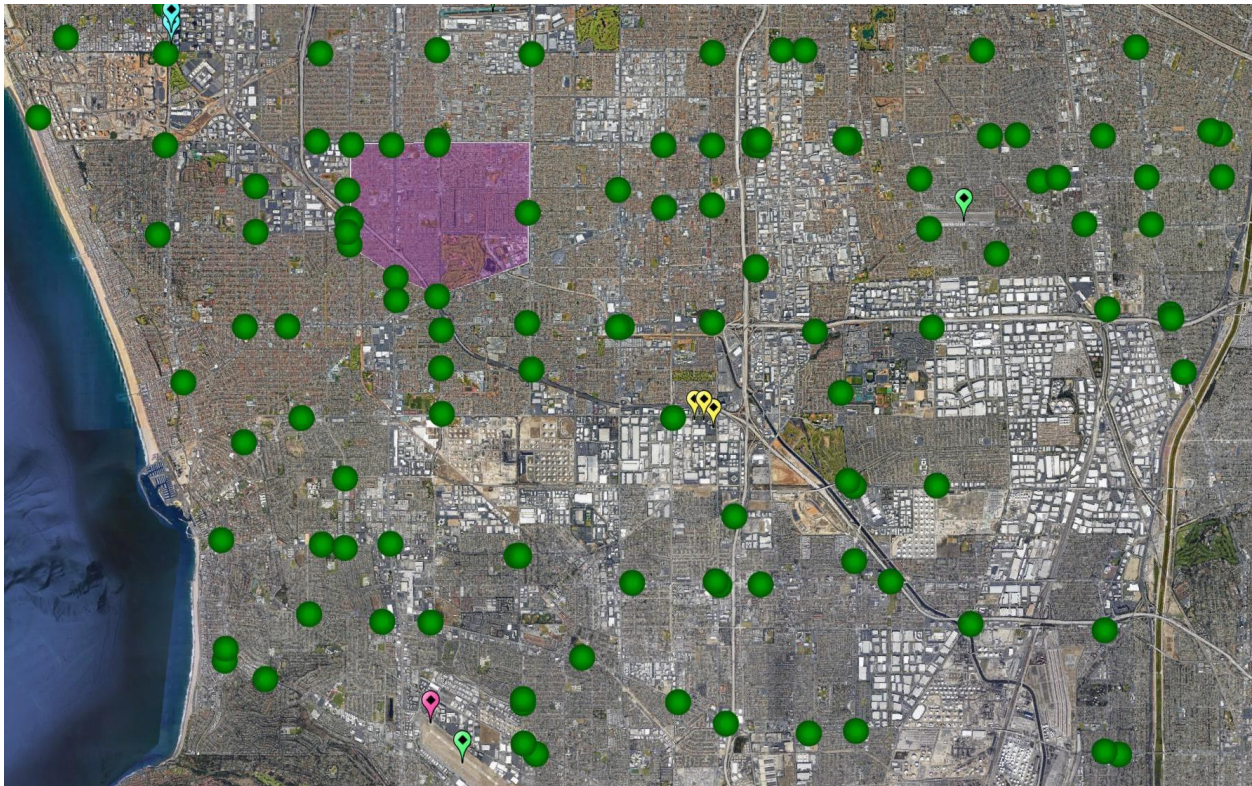


Figure 77. Potential geographic distribution of TOLAs (green circles) if co-located with gas stations. © 2016 Google. Map Data: USGS.

The pink region in Figure 77 represents an area that is relatively underserved by TOLAs co-located with gas stations. This area contains a dense suburban development and a university with no gas stations in the interior. The maximum driving distance from any location in this new reference area to a TOLA co-located at a gas station was just under one mile. While this represents a significant accessibility improvement over the currently available infrastructure, if ODM Aviation operations are to become truly ubiquitous then the first mile/last mile ground transportation must be reduced to less than 400 meters. This distance was determined by urban planners to be an acceptable walking distance for most individuals to public transportation modes [138], [139].

In order to further reduce the first mile/last mile travel distance within the reference area identified in Figure 77, the potential new TOLA infrastructure proposals from the right hand column of Table 43 were again reviewed. It was anticipated that any single TOLA in this reference area would not have high demand due to the suburban nature of the surroundings. As a result, TOLA proposals that required significant capital investment, such as facilities constructed over roadways or on the rooftops of businesses, may not be feasible from a cost perspective. Therefore, any 50 ft by 50 ft undeveloped, surface-level space such as parking lots, green spaces, or flood control channels were identified as potential TOLA locations. ODM aircraft with greater landing flexibility could possibly use these spaces, perhaps even without improvement, as operational sites.

Figure 78 indicates with orange circles the location of over 500 undeveloped spaces of at least 50 ft by 50 ft in dimension. As can be seen, a majority of these spaces were clustered in business parking lots around major roadways, on school grounds, at a golf course, or over a flood control channel. Although the location of TOLAs at any available 50 ft square clear space did not create an even geographic distribution of possible infrastructure throughout the reference area, the maximum ground travel distance within the reference area was reduced to approximately 1200 ft.

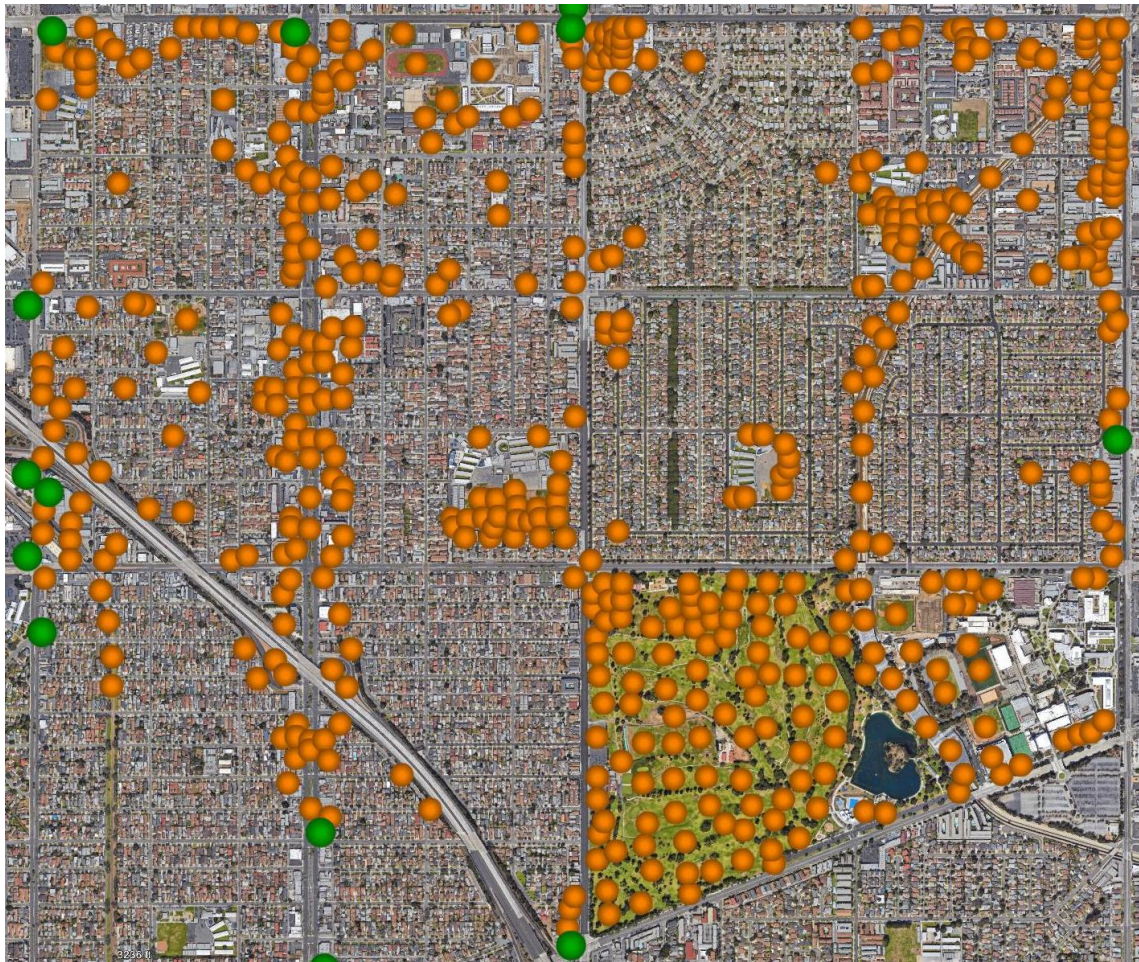


Figure 78. Potential geographic distribution of TOLAs if co-located with gas stations (green circles) and 50 ft by 50 ft surface-level undeveloped spaces (orange circles). © 2016 Google.

While the reduction of first mile/last mile travel distance to a TOLA from 1.7 miles to 1200 ft is a significant improvement and within the quarter mile acceptable walking distance of consumers, even this degree of TOLA availability does not necessarily provide ODM Aviation with the same convenience of automobiles. In order to reduce the first mile/last mile travel distance for ODM Aviation to be on the same order as that for personal or commercial cars, ODM aircraft must have the capability to land on roadways. The challenge of landing ODM aircraft on public roadways extends well beyond technical considerations and is discussed in Section 7.1.3.

Figure 79 displays a section of the reference area from Figure 78 that was relatively underserved by TOLAs co-located either at gas stations or in 50 ft by 50 ft surface-level, undeveloped spaces. The concentration of potential TOLAs in the center of the community is on the grounds of a public school, and therefore is unlikely to be developed as actual facilities. The line of TOLAs to the east of the community overlay a flood control channel. As indicated with red lines, if public roadways that do not have significant tree canopy coverage were utilized as TOLAs, ODM Aviation services could potential be brought to within 100 ft of any home.

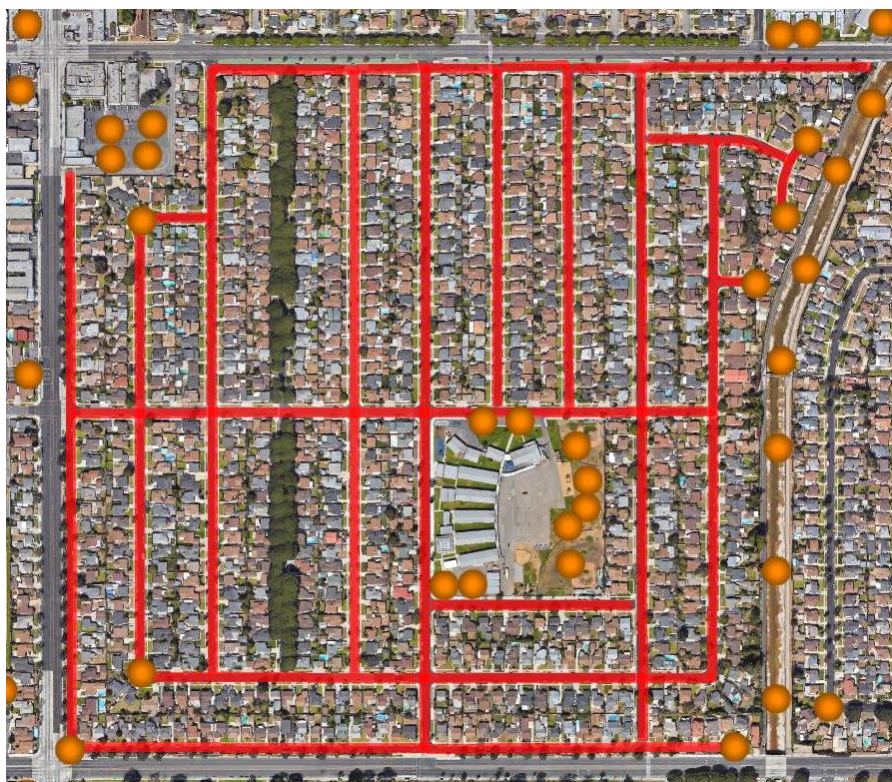


Figure 79. Potential geographic distribution of TOLAs if co-located with 50 ft by 50 ft surface-level undeveloped spaces (orange circles) and public roadways (red lines). © 2016 Google.

### 7.1.3 Feasibility of Proposed Approaches to Increase the Availability of TOLAs

The previous section reviewed the degree to which a set of proposed new infrastructure and vehicle takeoff and landing capabilities could potentially increase the availability of TOLAs to support an ODM Aviation network. While that analysis assessed the potential maximum geographic distribution of TOLAs that could be achieved through these potential mitigation proposals, it did not assess the overall feasibility of implementing any of those proposals. Implementation factors

including public acceptance, local and national regulations, unobstructed approach and departure pathways, development and maintenance costs, and utilization may inhibit the development of TOLAs in some locations. A brief review of the feasibility of developing TOLAs at the sites evaluated in ground infrastructure study in Section 7.1.2 was therefore conducted.

### 7.1.3.1 Influence of Aircraft Performance Limitations on TOLA Requirements

Current helipad design is driven in large part by two major vehicle performance considerations that must be accommodated for the safe takeoff and landing of helicopters. The first performance consideration is the design of approach and landing trajectories in a manner that avoids the development of a vortex ring state (commonly referred to as “settling with power”) during rotorcraft landing. Vortex ring state is a condition where rotor stall occurs as a helicopter descends vertically into its own downwash. This condition may require multiple hundreds of vertical feet to recover from, and therefore is hazardous if occurring at low altitudes such as during landing. In order to avoid entering a vortex ring state, standard takeoff and landing operations follow sloped trajectories rather than purely vertical paths.

The second helipad design-driving performance consideration is autorotation safety. In an engine-out scenario, helicopters may conduct an emergency landing maneuver known as autorotation which converts aircraft potential or kinetic energy into rotor inertia. In order to successfully complete this maneuver, the helicopter must be operating at sufficient velocity or height before the loss of power occurs. On a helicopter height-velocity diagram, such as Figure 80, a recommended takeoff and landing profile is provided that avoids operation in an unsafe region (often known as the “deadman’s curve”) where the vehicle has insufficient energy to conduct an autorotation.

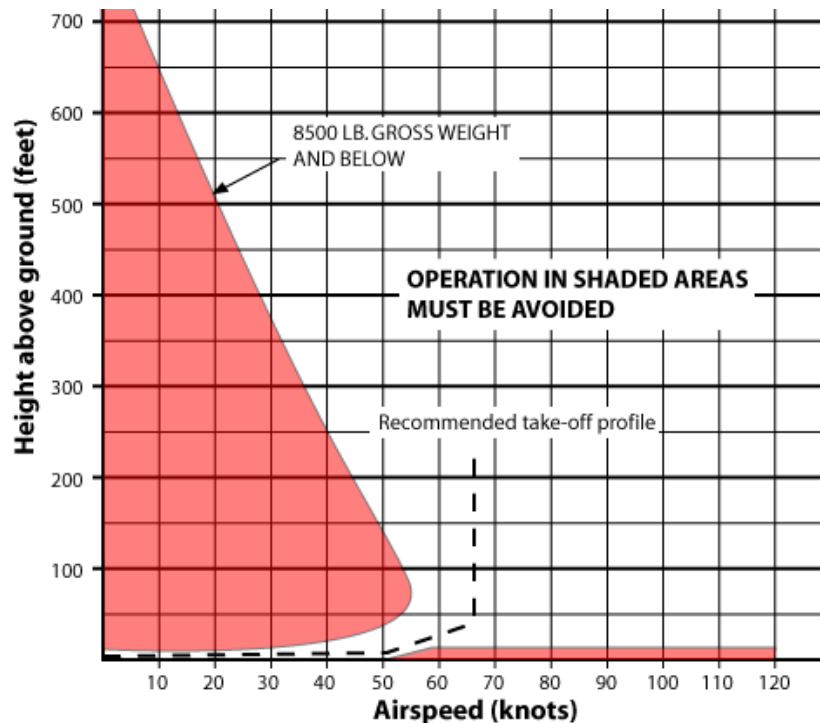


Figure 80. Height-velocity diagram for a Bell 204B helicopter displaying a recommended sloped takeoff profile and indicating in red the “deadman’s” curve. © BY-SA 3.0.

Both of these two performance challenges of helicopter flight therefore placed the need upon helipads to support sloped approach and departure trajectories. This need translated to heliport design standards that require specific approach and departure pathways to be certified and maintained clear of obstructions. Figure 81 displays current recommendations from FAA AC 150/5390-2C on heliport design that suggest heliports have at least two inclined approach and departure paths separated by an angle of at least 135° [195].

Many of the gas stations and 50 ft by 50 ft surface-level clear areas identified as potential TOLA locations in Figure 78 not only have obstructions in the immediate vicinity of the takeoff and landing area, but also have obstructions in neighboring properties. If these obstructions cannot be removed or avoided, then they may prohibit the certification of two approach and departure paths and the establishment of the TOLA. While the advisory circular is non-binding from an FAA standpoint, many local and state municipalities require in their ordinances or laws that aviation infrastructure be built to these standards, and insurance companies may also require them as a condition of coverage.

While these two performance challenges of flight may have historically hindered the development of helipads in dense urban areas, many proponents of ODM Aviation suggest that new VTOL aircraft could overcome these flight challenges of helicopters. For example, it has been suggested that full-electric, distributed propulsion aircraft do not have a single point engine failure mode and therefore will not have a “deadman’s” curve in their height-velocity operating curve. Therefore, such VTOL aircraft may not be required to approach and depart a TOLA with an inclined path [196].

Without this requirement these new aircraft may be capable of safely conducting strictly vertical descent from relatively high altitudes, thereby negating the need for large approach and departure surfaces at low climb angles. The validity of this argument remains to be tested, however, as single point electrical failures and other new failure modes could potentially cause hazard during extensive full-electric aircraft VTOL activities. Furthermore, it is unclear if distributed electric propulsion aircraft will be susceptible to vortex ring state development, and what envelope protections may be necessary to prevent unsafe operating conditions.

Beyond these two primary performance challenges of flight that influence the approach and departure surface size of future TOLAs, the stability of the aircraft and downwash velocity will also directly influence the minimum takeoff and landing surface size. A TOLA must be of sufficient size to safely contain an aircraft operation. For current helicopters, the minimum takeoff and landing surface size is 50 ft by 50 ft, and this surface is surrounded by an additional area (the final approach and takeoff area – FATO) that must be clear of obstructions reaching out to a hundred feet or more in some directions.

While future ODM aircraft technologies may provide greater stability and limit the downwash velocity of the vehicles, it is unclear how much the size of TOLAs will be able to be reduced, especially when considering security measures that may be necessary for surface-level facilities.

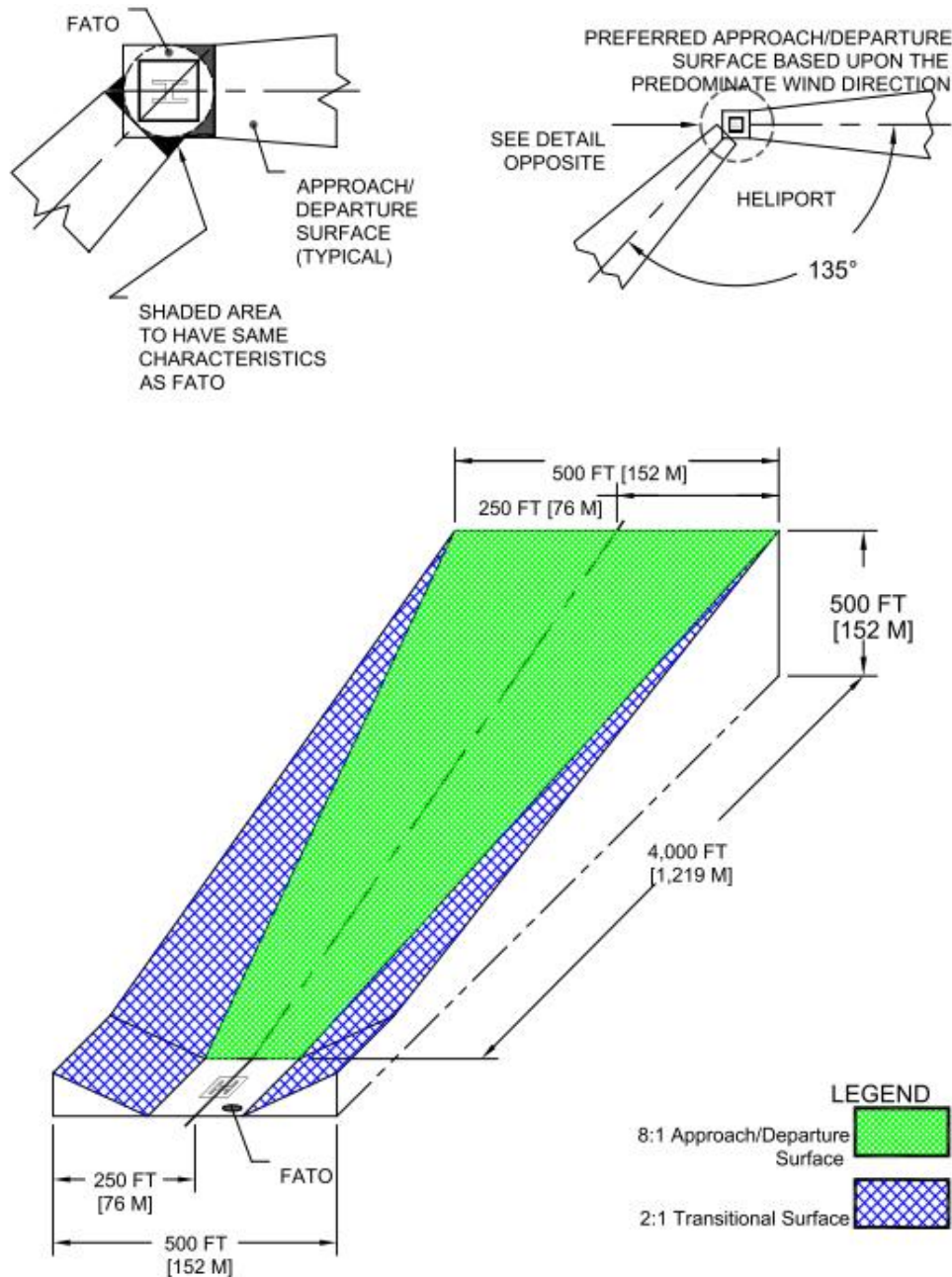


Figure 81. VFR heliport approach/departure and transitional surfaces. *Image created by the FAA and retrieved from AC 150/5390-2C: Heliport Design [195, p. 75].*

### 7.1.3.2 Regulatory Influence on TOLA Development

Perhaps the most significant near-term challenges for the development of new TOLA infrastructure are local municipality and state regulations. Local regulations vary significantly from locality to locality and would require an ODM operator to conduct a detailed study of each proposed area of operation. For the purposes of this thesis a review of the state and local municipality regulations affecting infrastructure development in Los Angeles County was conducted to provide insight into the types of near-term development limitations regulations may



impose. The findings from this regulatory review may in some cases be applicable to other counties in California, but in general should not be applied to other municipalities without review of any additional local aviation infrastructure development and operation regulations.

Table 44 presents three regulations that place restrictions on the certification of new TOLAs. These regulations are from the California Public Utilities Code (PUC) and the California Code of Regulations (CCR).

Table 44. Regulations that potentially create TOLA certification challenges.

| Regulation    | Description   |
|---------------|---|
| PUC § 21661.5 | City councils and county boards of supervisors (or their designees) must approve every TOLA in their boundaries   |
| PUC § 21666   | Requires every TOLA certification conduct an environmental study that includes noise, air pollution and ground surface traffic impact, among other aspects                                      |
| CCR § 3533(b) | Temporary helicopter landings sites are exempt from permitting requirements, but cannot be used for more than a year and must be granted authorization by CALDOT (an onerous process in itself) |

These three regulations suggest three important factors for the establishment of new TOLAs. First, PUC § 21661.5 empowers local government and citizens to weigh in on the development of any new TOLA with the right to prohibit its development. This implies ODM Aviation operators may have to directly work with each community in which they intend to offer services.

Secondly, PUC § 21666 requires that every new TOLA have a unique environmental study conducted prior to its approval. While it is unclear how expensive such a study may be, the inclusion of air pollution, noise exposure and surface traffic impact studies appears to suggest a relatively involved (and expensive) study is required.

Finally CCR § 3533(b) provides a route that TOLAs could be established for temporary events (such as concerts, games or film festivals), however this process requires specialized approval from CALDOT that requires additional paperwork and levies further operating limitations.

Taken as a whole, these three regulations impose significant challenges on the development of new TOLAs. Furthermore, the ability of local authorities to block the development or operation of a TOLA at-will places great uncertainty on where ODM Aviation services will be able to expand to. Considering this factor in particular, TOLAs may have to be constructed on a case-by-case basis following negotiation with the local municipal government. Developing the thousands to tens of thousands of TOLAs necessary to provide ubiquitous ODM air transportation for an area as large as the Los Angeles basin may be a monumental challenge due to regulatory compliance.

The regulatory situation surrounding “off-airport/heliport” landings not at certified facilities is equally challenging. Table 45 presents three additional regulations that influence these types of operations.

Table 45. Regulations that potentially restrict off-TOLA operations.

| <b>Regulation</b> | <b>Description</b>  |
|-------------------|---|
| PUC § 21403(b)    | Non-emergency, unapproved landing on a public road is not permitted   |
| PUC § 21403       | Must have consent of property owner to make a non-emergency landing   |
| PUC § 21662.5     | No helicopter may land or depart within 1000ft of a school maintaining K-12 classes except at a permitted permanent heliport without completing a strenuous approval process requiring 15+ days and community hearings at the impacted school |

The first of these regulations explicitly removes the potential for ODM Aviation to land on public roads and provide services with geographic coverage as complete as that of the automobile. While some potential may exist to gain permission from CALDOT for specific operations, this will likely require significant preparatory work and road closures making it unsuitable for standard on demand operations. Secondly, PUC § 21403 empowers landowners to directly control if operations are conducted to or from their property.

PUC § 21662.5 is an especially interesting regulation with profound consequences for ODM operations at non-certified TOLAs. Figure 82 displays the influence of this regulation showing that roughly 45% of the land area within the pink reference area (a dense suburban development of 2.9 square miles) lies within 1000 ft of a K-12 school. As a result, no aircraft could conduct on demand operations to an off-airport TOLA within any of the red shaded areas due to the required multi-week approval process. This regulation, which applies to the entire state of California, significantly limits the areas where ODM operations may be conducted without certified TOLAs.

A final regulatory consideration unveiled through this study was the legal “grey area” for operations that do not physically land or takeoff from an area, but transfer goods or people while in hover. This practices is not a capability of current vehicles, therefore it has not been directly addressed. As such, the regulations presented in Table 45 apply only to operations that physically alight on the surface. Therefore, it may be the case that an aircraft that conveys passengers or goods by lowering a basket, gondola or ladder without ever landing could technically circumvent the regulations as presented. Of course, even if technologically if possible, this operation would likely prompt rapid updates to the regulations and may incite penalties from other statutes concerning reckless operation or public endangerment, for example.

[Intentionally Left Blank]

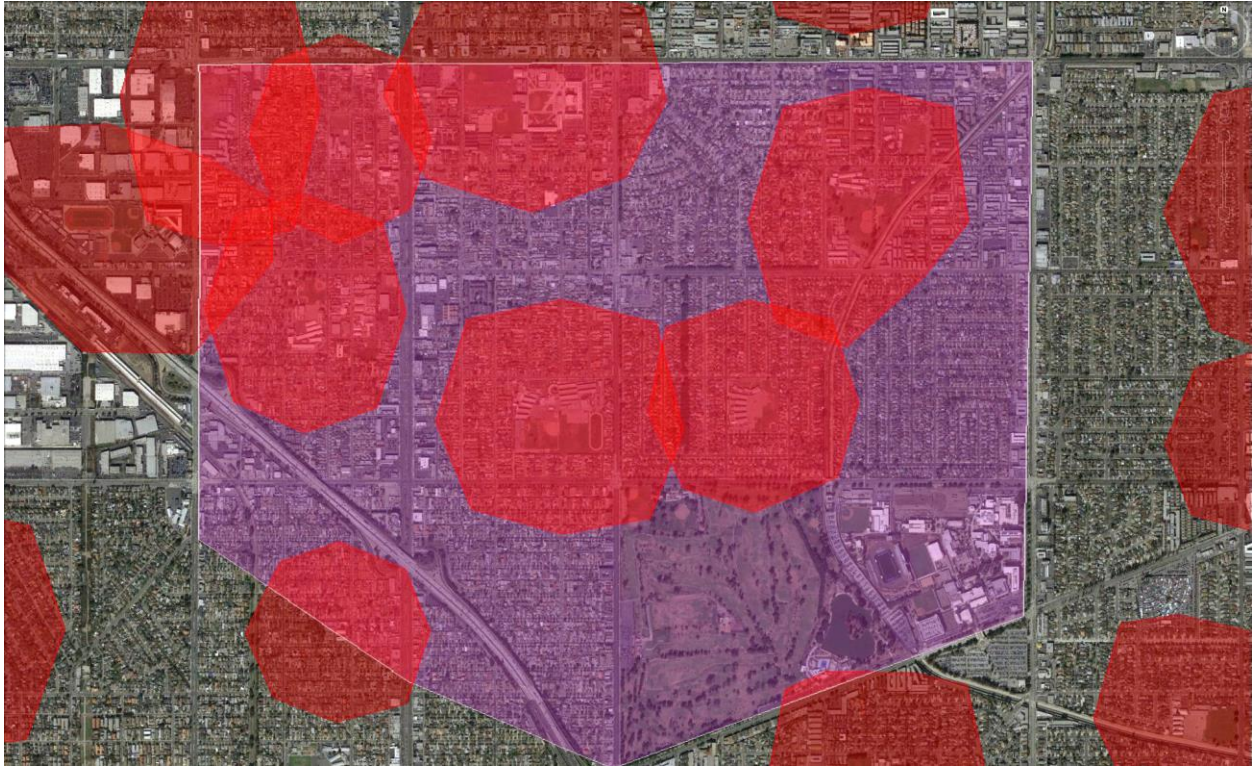


Figure 82. Impact of PUC § 21662.5 regulation which prohibits aircraft landings within 1000 ft (indicated in red) of a K-12 school, except at an approved TOLA facility. © 2016 Google.

### 7.1.3.3 Community Acceptance Influence on TOLA Development

Local communities have significant influence over the ultimate location of TOLAs through the required approval of their elected municipality governments. As a result, gaining community acceptance for ODM Aviation operations and infrastructure is a key step towards mitigating the overall TOLA availability constraint. Individuals may disapprove of aircraft operations in their community for a variety of reasons including noise, vibrations, privacy, viewshed, emissions, dust and safety concerns. Some of these concerns, such as noise, vibrations and emissions may be lessened by new vehicle technologies. Dust creation may also potentially be eliminated through TOLA design. However, privacy, viewshed and safety concerns are more nebulous and may only be possible to address on a case by case basis with individual communities.

Chapter 6 reviewed the legal and regulatory factors surrounding low altitude aviation operations to clarify what rights landowners may have to limit flight over their properties. However, even if pilots are confirmed in the court system to have significant overflight privileges, communities may still restrict landing and takeoff operations in their jurisdiction. Therefore, community acceptance is a challenge for the development and operation of ground infrastructure which there may be no pure technological solution for. For this reason, it is especially important that ODM Aviation operators do not prematurely begin operations in the near-term before communities are prepared to accept them. A rushed entry to market without appropriate public relations groundwork could skew public opinion against intra-urban aircraft operations and create inertia behind regulations and laws that stunt the far-term growth of ODM Aviation networks.

#### *7.1.3.4 Business Influence on TOLA Development*

A final challenge for increasing the availability of TOLAs is the business factors of developing new aviation ground infrastructure. While creating a large, geographically distributed network of TOLAs is likely to increase consumer demand for the service (by reducing first mile/last mile transportation) while simultaneously increasing the network supply of the service (by increasing aircraft throughput in a region), each TOLA also represents a carrying cost to the network. Beyond initial capital investment for construction and certification, TOLAs must be maintained, may require on-site staff or security, and will be subject to taxes, rent, insurance and other potential costs.

Therefore, for reasons of financial solvency, the ultimate number of TOLAs in an ODM network will balance the marginal increase in demand with the marginal increase in carrying costs due to each new facility. For these reasons, it is likely that initial ODM aviation markets will rely upon existing single-pad TOLAs and invest in high-capacity TOLAs in areas of high demand. As the service becomes widely accepted and demand increases, community opposition to TOLAs may be diminished allowing for a less costly expansion of the network to markets in other geographic areas.

#### **7.1.4 Summary of Mitigation Potential for TOLA Availability**

The review conducted in this section identified numerous proposed mitigation techniques that have the potential to significantly increase the availability of TOLAs. However, significant challenges exist for the implementation of the mitigation techniques proposed including aircraft performance, regulatory, community acceptance and business challenges. New technologies, especially electric aviation, show promise to reduce or overcome some of these challenges, however others remain. Aircraft noise, an ODM Aviation constraint in its own right, is of particular importance to TOLA availability as it heavily influences community acceptance and regulatory compliance.

TOLA availability represents a classic “chicken and egg” conundrum. ODM Aviation networks can only attract and service a large base of customers once a geographically distributed set of TOLAs is implemented with sufficient capacity. However, the financing and market acceptance of a geographically distributed set of TOLAs may only emerge once the benefits of ODM Aviation are widely acknowledged through the successful implementation of these services. Recognizing this challenge, ODM operators may benefit from beginning services along specific routes or corridors with limited infrastructure requirements to gain experience and build positive public sentiment. Additionally, investors or businesses with geographically diverse storefronts may capture entire new markets by investing in TOLA development and certification and leasing access to the emerging ODM operators.

## ***7.2 Scalability of ODM Networks under Air Traffic Control***

The second constraint for ODM Aviation concerned whether Air Traffic Control could be scaled or supplemented to support a significant increase in the number and density of low altitude aircraft operations (due to ODM services as well as UAS activities). While current ATC capacity is sufficient to support one-off ODM operations and early adopter market activities, the system is anticipated to become overburdened as ODM networks scale. This could create capacity or access limits for ODM aircraft throughput to specific surface-level airspaces and ground locations.

Considering these factors, while ATC scalability for low altitude operations is not necessarily a near-term constraint, mitigation efforts for ATC scalability should be explored in the near-term as improvements to ATC have historically occurred over long time scales.

The scalability constraint for ATC was decomposed into three separate but related challenges displayed in Table 46. This decomposition allowed for a clearer evaluation of how potential mitigation approaches addressed or failed to address the specific challenges of ODM network scalability under ATC.

Table 46. Challenges for the scalability of ATC to support low altitude aircraft operations.

| <b>ODM ATC Scalability Challenge</b>                                | <b>Description</b>   |
|---|--|
| Access to Controlled Airspace<br>( <i>ATC controller workload</i> ) | 92% of the ODM reference missions in L.A. required entrance into a class B, C or D surface-level airspace. Such operations require contact with an air traffic controller. A significant increase in the number of ODM or UAS flights requesting access to controlled airspace may overwhelm the current system’s capacity preventing entry to these airspaces.    |
| High Density Operations<br>( <i>maximum throughput</i> )            | Existing radio-frequency communication modes may not provide sufficient capacity to support high density aircraft operations. Furthermore, ATC separation standards in controlled airspaces may restrict maximum ODM aircraft throughput.  |
| Heterogeneous Aircraft Operations                                   | Helicopters, ODM aircraft and UAS will likely be required to operate simultaneously in shared airspace over dense metropolitan areas. The FAA recorded 1200 incidents of UAS close calls with aircraft in 2015, and it is unclear if the accuracy of spatial and temporal locating technologies are sufficient to support dense, heterogeneous aircraft operations |

### 7.2.1 Current Low Altitude ATC Proposals

Spurred primarily by the desire to support low altitude UAS operations and integrate UAS into the national airspace system, the aviation community has developed a variety of proposals to address low altitude ATC scalability. While the size and payload of ODM aircraft and UAS are quite different, the actual mission profiles of the vehicles are relatively similar. Therefore, the new technologies and ATC approaches proposed for UAS may be directly applicable, or at least informative, to address this ODM constraint.

Furthermore, while the FAA is not currently considering an airspace restructure to accommodate UAS, significant analysis and development has been conducted by private entities, NASA and the FAA on this subject [197]. As the UAS community is the first mover many years before ODM Aviation, it is likely that ATC and airspace changes to support low altitude ATC scalability will be driven by the UAS community rather than the ODM community. The ODM community should therefore evaluate the proposed mitigations, provided in Table 47, and contribute to their development such that these approaches may serve the future needs of both UAS and ODM aircraft.

Table 47. Proposed approaches to low altitude ATC scalability.

| <b>Proposed Approach</b>                         | <b>Description</b>  |
|--|---|
| Airspace Segregation by Aircraft Capability      | Low altitude airspace is segregated, typically through altitude stratification, to permit aircraft (or UAS) of similar type, equipage and performance capabilities to fly in common corridors   |
| Airspace Allocation to Requested Operations      | Dynamic or static allocation of reserved airspace “zones” are granted to requestors by a central airspace controller. Only a single operator is allowed in a reserved zone. This approach is commonly referred to as geofencing   |
| 3 <sup>rd</sup> Party Airspace Service Providers | Traffic separation and route planning is provided by a non-governmental, 3 <sup>rd</sup> party airspace service provider. Approaches to separation and route planning range from pre-planned, centralized route optimization by the service provider to “free flight” concepts with communications and real-time deconfliction conducted by on-board software |
| FAA ATC Expansion and Automation                 | Expansion and automation of current FAA ATC capabilities (as part of NextGen or beyond) to manage high density, low altitude operations in controlled airspaces   |

While each of these proposed mitigation approaches may provide significant increases in ATC capabilities compared to the current system, they lack specific considerations that will be necessary to support ODM Aviation operations.

First, none of these proposals anticipate a significant increase in the number of manned flights in low altitude airspace, but rather focus primarily on UAS operations. As a result, the airspace segregation and airspace allocation approaches generally relegate manned operations to flight above 500 ft AGL and reserve, or at least prioritize, the lower altitude airspaces for UAS operations. While UAS operations are not permitted near existing airports where manned aviation is prioritized, ODM aircraft seeking to access new TOLAs or off-airport TOLAs may encounter denial of entry or long wait times due to these low altitude ATC approaches.

In order to prevent the lock-in of an ATC system that does not effectively consider the interaction of manned aircraft and UAS in low altitude airspaces, the ODM and UAS communities may need to coordinate approaches to handle flight priority and access to airspaces or flight corridors, especially in on-demand service situations.

The second gap in the proposed ATC scalability approaches is that some of the approaches may inefficiently use airspace and lead to denial of access for some ODM operations. By allowing for the individual allocation of airspace through geofencing, or designating specific altitude bands that are available only for certain types of aircraft or operations, airspace is segmented and unavailable to some operators in this proposal. The capability to reserve airspace through geofencing (especially if reservation lead times are long) are counter to the needs of an on-demand service. Furthermore, designating large blocks of airspace for only a single operation, or only for a specific type of aircraft, may reduce throughput potential to that airspace and the surface area it covers.

While geofencing and airspace stratification may be necessary in the near-term to provide for the safe operation of UAS and manned vehicles, as technologies and experience improve these systems may need to be relaxed to enable the more efficient, simultaneous use of airspace by aircraft in close proximity to other operations.

The final gap in the current ATC enhancement proposals is that except for the FAA ATC expansion proposal, none of the approaches addressed low altitude flights within Class B, C, D or E controlled airspaces. The reference missions from the L.A. case study suggested a significant number of ODM Aviation operations may require access to surface-level controlled airspaces. Figure 83 displays the surface-level controlled airspaces in the Los Angeles basin in yellow. These airspaces cover approximately 43% of the densely populated metropolitan area which is shaded green in the figure.

In order to provide ODM Aviation operations with consistent access to low altitude airspace, additional mitigation efforts should be developed, or the currently proposed approaches enhanced to support operations in controlled airspaces. Section 7.2.2 investigates potential approaches to better enable ODM aircraft and UAS access to low altitude, controlled airspaces.

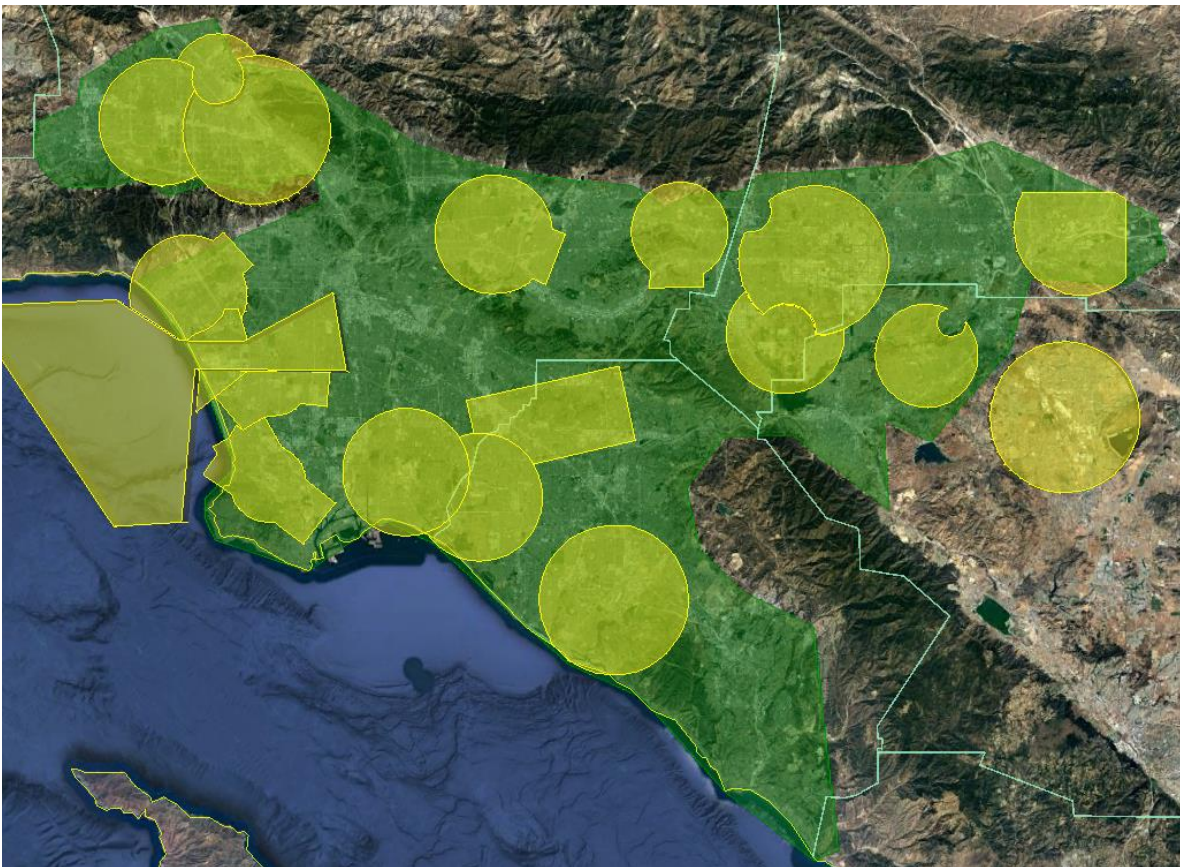


Figure 83. Surface-level controlled airspaces (yellow) cover 43% of the densely populated areas (green) in the L.A. basin.

© 2016 Google. Map Data: LDEO-Columbia, NSF, NOAA, SIO, U.S. Navy, NGA, GEBCO.

## 7.2.2 Investigation of ATC in Low Altitude Controlled Airspaces

To better understand opportunities to improve ATC scalability in low altitude controlled airspaces, the present-day aircraft operations in the Los Angeles basin were first reviewed. Twelve months of flight tracking data from the Los Angeles International Airport (LAX) was collected and analyzed to identify the flight patterns of general aviation aircraft, helicopters and commercial aircraft. It was anticipated that a review of flight data may reveal trends for each class of operation to inform how a significant number of new ODM flights could be integrated into the airspace.

### 7.2.2.1 Review of LAX ASDE-X Flight Trajectory Data

ASDE-X, or Airport Surface Detection Equipment Model X, is an advanced aircraft surveillance system that is installed at 35 of the busiest airports in the United States. The system uses multiple data sources to provide high quality flight tracking data to air traffic controllers with a maximum update time of 4.65 seconds. The system has a coverage area of roughly 10 nmi around the equipped airport and is commonly recognized as a useful tool to support the analysis of operations in the vicinity of such airports.

To support the analysis, ASDE-X flight tracking data from LAX covering the period of April 1, 2015 through March 31, 2016 was evaluated. The data was refined to resolve anomalous data points, discard days with incomplete data, and smooth the recorded flight trajectories. The resultant data set contained 203 days of flight trajectory data for 536,000 aircraft flights. Figure 84 displays the coverage area of the LAX ASDE-X data. The blue circle represents the airport location and the surface-level Class D airspaces are indicated with dark red while the surface-level Class B airspaces are indicated in bright red.

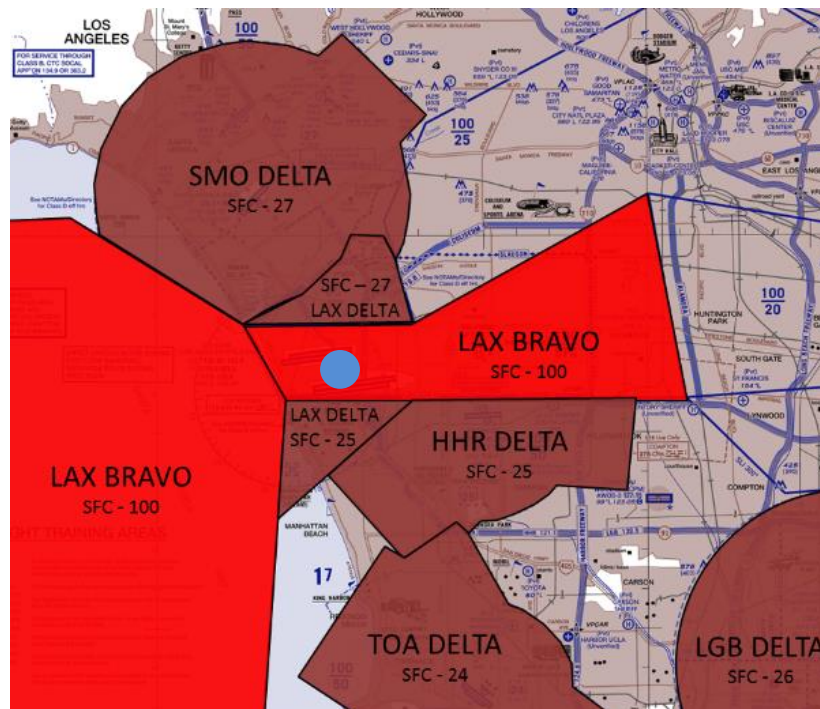


Figure 84. LAX ASDE-X radar coverage with surface-level airspaces indicated in red and the airport location indicated in blue.



The final 536,000 ASDE-X flight trajectories were aggregated and plotted onto a two-dimensional heat map with axes of latitude and longitude. Since flight trajectories also have a third dimension of altitude, multiple heat maps were created where each one covered a 200 ft altitude slice spanning from 300 ft AGL (measured from the LAX elevation) up to 12,000 ft AGL. Each cell, or 3D bin, of the heat map was roughly 200 ft by 200 ft in dimension and covered 200 ft of altitude.

Figure 85, Figure 86 and Figure 87 present three altitude slices of the ASDE-X data displaying the annual density of flights near LAX at 300 ft, 700 ft, and 1500 ft, respectively. “Hot” airspace cells are indicated in yellow and represent areas where at least 400 flights per year flew; the maximum flight density in a cell was over 80,000 flights per year. Surface level controlled airspaces are outlined in green, and airport runways are indicated by red bars. Key aspects of the figures have also been indicated.

The primary takeaway from the ASDE-X analysis was that there exists highly concentrated corridors of commercial operations off the ends of the runways (on SID and STAR routes) with sparse, distributed General Aviation (GA) and helicopter flights throughout the rest of the region. The GA and helicopter operations concentrate into specific corridors to pass through the LAX Class B airspace, but otherwise are far more distributed. Finally, a majority of the evaluated airspace has no commercial flights and few to no GA or helicopter flights over the course of the period analyzed. This suggests that the percent of the airspace being actively utilized for flight may actually be relatively low and it may be possible to add a large number of new ODM flights without dramatically altering current airspaces or operations.

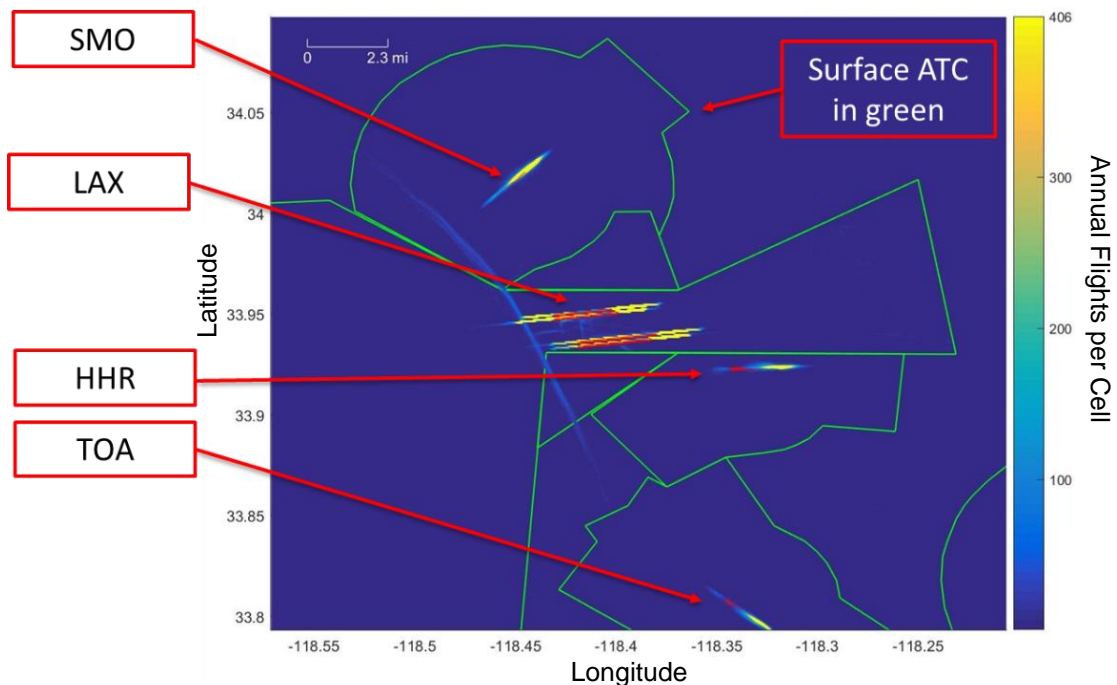


Figure 85. LAX ASDE-X annual flight density heat map for an altitude slice of 300 ft to 500 ft.

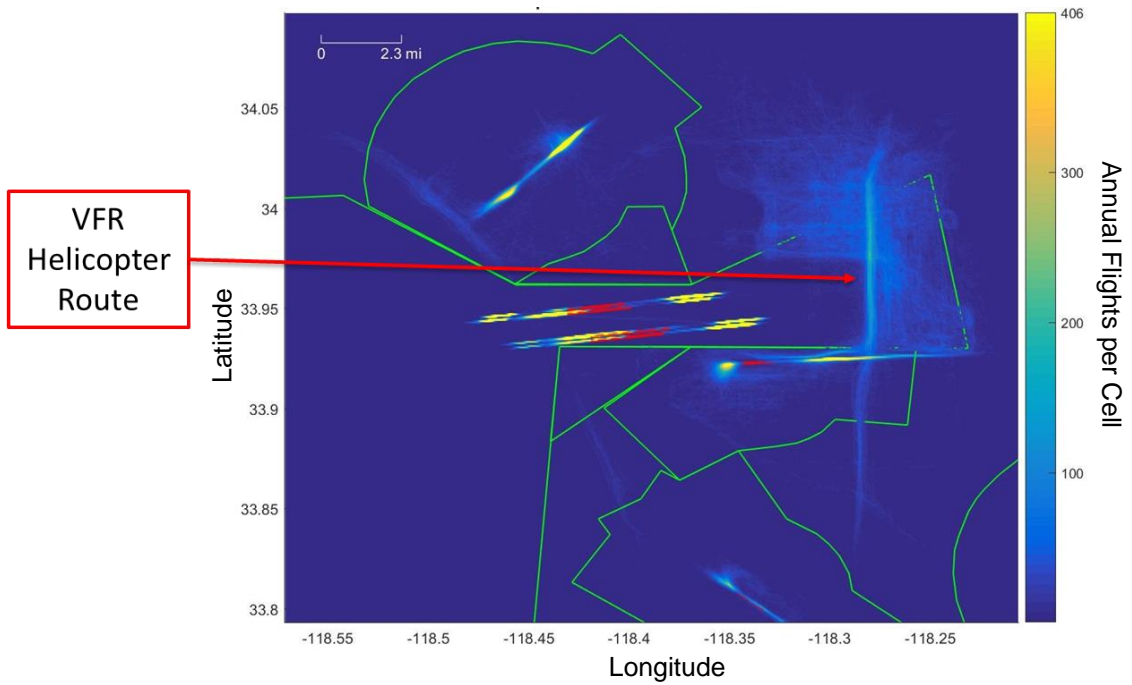


Figure 86. LAX ASDE-X annual flight density heat map for an altitude slice of 700 ft to 900 ft.

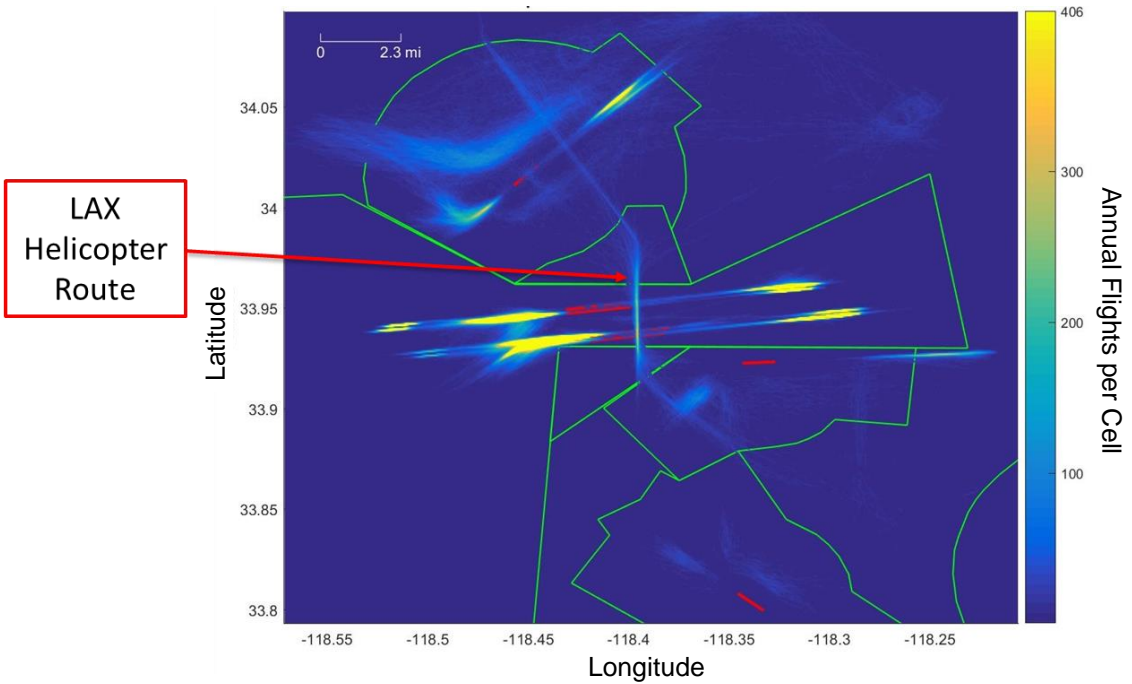


Figure 87. LAX ASDE-X annual flight density heat map for an altitude slice of 1500 to 1700 ft.

### 7.2.2.2 Controlled Airspace Utilization in Los Angeles

A primary finding from the review of the ASDE-X flight trajectory data was that a majority of airspace over L.A. currently supports no commercial flights and few to no GA or helicopter operations. To better evaluate this finding, an “airspace utilization” metric was defined. A cell of airspace (roughly 200’ by 200’ by 200’) was considered to be utilized if it contained at least 5 flight trajectories per year. Figure 88 displays the resulting findings for airspace utilization of the LAX airspace.

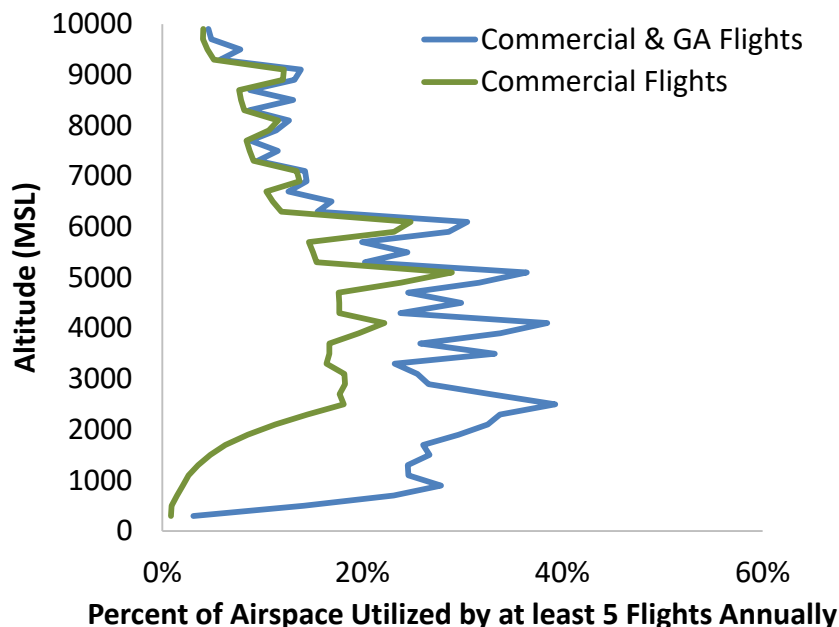


Figure 88. Los Angeles basin airspace utilization by commercial and GA operators.

Perhaps the most immediately recognizable feature from Figure 88 was the significant difference in airspace utilization of commercial operations and GA operations at low altitudes. For airspace below 2500 ft MSL, commercial aircraft accounted for 430,000 annual flights and utilized only 5% of the total airspace. However, when GA and helicopter flights were also considered, the total number of annual flights increased to 536,000 and the airspace utilization rose to 24%. Within this region, surface-level ATC covered 61% of the airspace.

### 7.2.3 Dynamic, Fine-Scale Airspace Allocation

The relatively low utilization of airspace compared to the relatively large percent of surface-level controlled airspace is a result of the current approach to ATC. Controlled airspaces were designed to contain all published procedures including different runway configurations and missed approaches. Furthermore, the controlled airspaces were enlarged to provide margins of safety and act as a buffer for potential intruding aircraft. The ASDE-X data review revealed that the runway configurations are stable within Los Angeles due to the consistent weather and wind patterns, and abnormal operations for missed approaches or go-arounds are infrequent. Therefore, it appeared that the full extent of the controlled airspaces were rarely, if ever utilized.

Considering this finding, new airspace management and communications technologies may create the opportunity for dynamic, fine-scale airspace allocation in the near to long-term. This style of airspace management could support the scale-up of low altitude ATC within controlled airspaces by better managing traditionally underutilized areas.

Dynamic, fine-scale airspace allocation involves the creation of a pre-defined airspace volume(s) within a controlled airspace. The airspace within the volume has similar utilization characteristics based upon the ATC patterns in use at the airport. For example, the volume of airspace to the east of the four LAX runways contains the primary approach pathways during the daytime, but from midnight to 6:30am airport policies prohibit any non-emergency westbound approach patterns. This volume of airspace essentially has zero utilization during these hours.

The core concept behind dynamic, fine-scale airspace allocation is that air traffic controllers are given the capacity to “open” or “release” a pre-defined airspace volume that is not required for the current ATC configuration. A released airspace volume could then be made available for flight to properly equipped aircraft operating under special flight rules; these aircraft would likely not be required to contact ATC to fly in the volume. Essentially, the core concept of dynamic, fine-scale airspace allocation is to allow air traffic controllers to create *temporary* Special Flight Rules Areas (SFRAs) within underutilized areas of controlled airspaces in order to ease their workload.

Numerous SFRAs have been implemented around the country. A SFRA resides over LAX passing through the Class B airspace of the airport overtop the runways. It supports up to hundreds of VFR aircraft and helicopter flights per day without placing any additional workload on ATC. Similarly, the Hudson River SFRA in New York allows hundreds of helicopter tours and commuters to operate well within the La Guardia Class B airspace without ATC contact. Due to the similarities between SFRAs and dynamic, fine-scale airspace allocation volumes, this research has elected to call these new volumes “Dynamic Flight Rules Areas”, or DFRA.

Figure 89 displays a conceptualization of how DFRA could be defined and implemented at the Bob Hope airport in Burbank, just north of Los Angeles. The primary runway configuration for the airport accounts for over 96% of all operations through eastbound arrivals and southbound departures. With this configuration, three notional DFRA could readily be defined to the north, southwest and southeast of the airport. When released by ATC, properly equipped ODM aircraft or UAS could gain access to as much as 50% of the Burbank Airport Class C airspace without placing further workload requirements on ATC. If the airport were to change runway configuration or otherwise need to recover a DFRA (such as for an abnormal operation), ATC could rescind the DFRA allocation and open up alternative DFRA if possible, as displayed in Figure 90.

When open for operation without ATC services, the DFRA could potentially be managed in a variety of ways. Currently, the SFRAs are operated under visual flight rules with special radio frequencies and, in some cases, specific required flight patterns to provide enhanced safety. Such a system may initially be appropriate for DFRA. However, as ODM, helicopter and UAS flight densities at low altitude increase it may be necessary to adopt one of the more sophisticated airspace management approaches proposed in Table 47. In particular, the NASA Unmanned Aircraft System Traffic Management (UTM) program is developing a communications network for UAS that may be useful in the near-term to organize heterogeneous operations in the DFRA and convey high-level oversight information back to ATC.

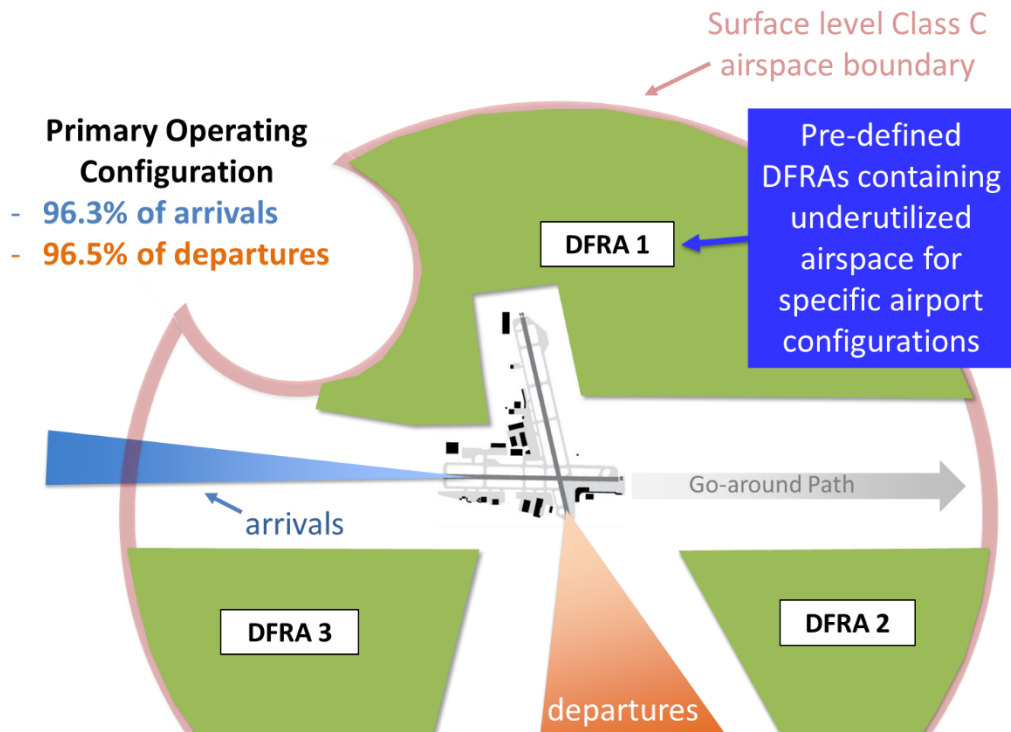


Figure 89. Notional diagram of dynamic, fine-scale airspace allocation with dynamic flight rules areas (DFRAs) for Bob Hope airport in the primary runway operation configuration.

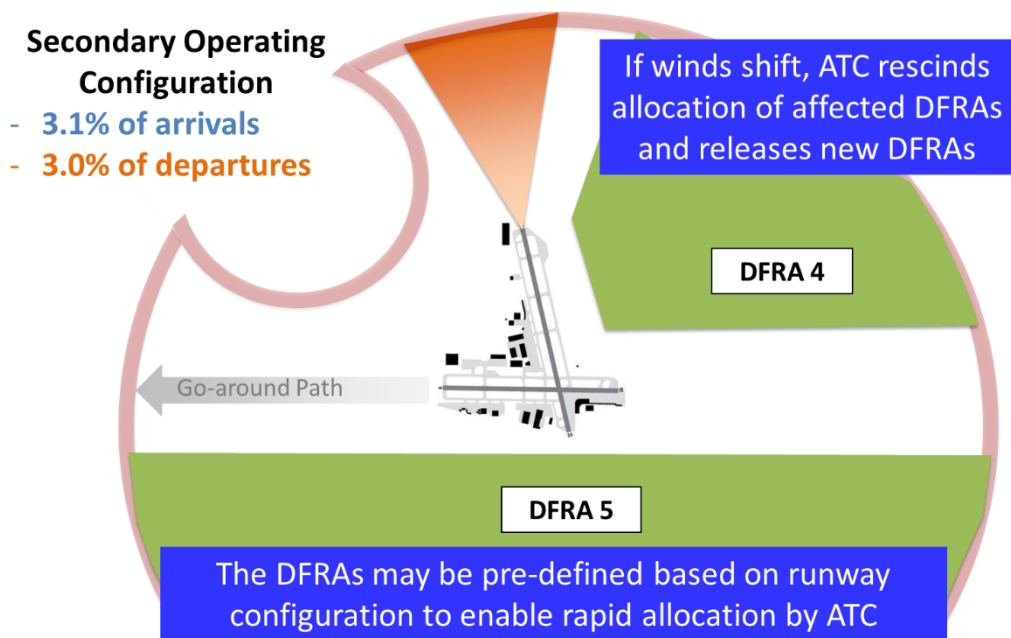


Figure 90. Notional diagram of dynamic, fine-scale airspace allocation with dynamic flight rules areas (DFRAs) for Bob Hope airport in the secondary runway operation configuration.

The dynamic, fine-scale airspace allocation scheme proposed above as a mitigation approach for ATC scalability in controlled airspaces prompted numerous research questions concerning implementation and safety. Table 48 displays a set of three key questions ripe for future research to assess if dynamic, fine-scale airspace allocation could be a feasible mitigation approach.

Table 48. Dynamic, fine-scale airspace allocation architecting and implementation questions.

| <b>Questions</b>     | <b>Description</b>   |
|----------------------|--|
| Communications       | How will information regarding the status of the DFRA be communicated? What information exchange protocol will exist between ATC and either the DFRA airspace service provider and/or the individual aircraft in the DFRA? |
| DFRA Vacate Time     | What is the latency time necessary to close and clear a DFRA of aircraft if ATC must regain control of the volume?   |
| Separation Standards | How accurately can UAS and aircraft position be measured spatially and temporally, and how will separation standards evolve in DFRAs with increasingly dense operations?   |

While the communications question will likely be resolved for low-density operations through reserved radio frequency channels (such as is done in SFRAs) and for high-density operations through a third party airspace service provider, the DFRA vacate time and separation standards questions are less clear-cut.

Unlike SFRAs, which are permanently open to VFR operations without required ATC contact, for a variety of reasons it may be necessary for ATC to close a DFRA and vacate all aircraft from the volume. Furthermore, some events, such as a missed approach by a large aircraft, may require ATC to rapidly close and vacate the DFRA without warning or lead time. Equipment and performance requirements may therefore be levied on aircraft seeking to operate in the DFRA to ensure they are capable of vacating the volume within an acceptable period. Table 49 displays a list of potential events requiring DFRA closure, and a listing of the projected lead time ATC may have to close and vacate a DFRA to ensure safety for each event.

Table 49. DFRA closure event description and characteristics.

| <b>DFRA Closure Event</b>               | <b>Lead Time</b>   | <b>Frequency</b> |
|---|--------------------|------------------|
| Runway change for wind shift            | 30 minutes         | Hourly           |
| Runway change for noise abatement       | Scheduled          | Daily            |
| Runway change for weather               | 30 minutes         | Daily            |
| Emergency operation (EMS, fire, police) | Minutes            | Infrequent       |
| Missed approach/go-around               | Seconds to minutes | Daily            |

The other research question of significant interest concerns one of the primary factors influencing the maximum throughput potential of an airspace: the separation standard that is used for aircraft operating in that area. Figure 91 displays three current separation standards showing how new ATC technologies have reduced the separation requirements for aircraft in controlled airspace. VFR standards, on the other hand, are written so as to place separation responsibility on the pilot.

This trend suggests that the safe operation of aircraft in proximity to one another is dependent upon accuracy of the aircraft positioning and sensing technologies.

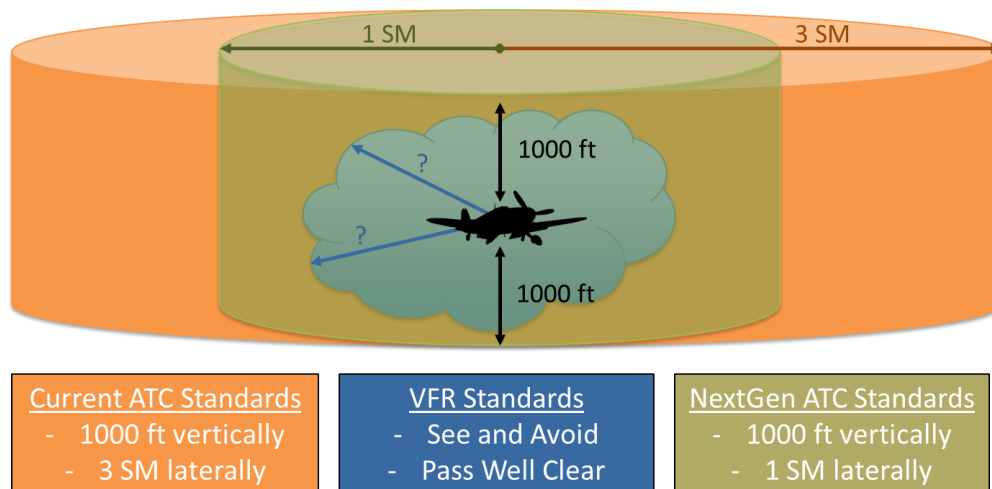


Figure 91. Current aircraft separation standards for low altitude operations.

Separation minima avoid aircraft conflicts (both under ATC separation or self-separation) by accounting for inaccuracies in spatial and temporal location reporting. Improved geo-locating technologies through GPS have reduced position uncertainty compared to radar tracking. This enabled NextGen to reduce separation standards for aircraft operating under ATC. Onboard collision avoidance systems such as ADS-B have also supported the reduction of these separation standards and increased the safety of self-separated VFR traffic.

Currently, flight density in controlled airspaces is limited both by the separation minima as well as the air traffic controller workload. Dynamic, fine-scale airspace allocation has shown potential to mitigate air traffic controller workload in a significant percentage of surface-level controlled airspace, and new geo-locating technologies may reduce the separation minima required within the DFRA. Figure 92 displays a notional system architecture pathway through which ODM aircraft flight density could be increased in surface-level ATC airspaces.

First, one-off ODM Aviation missions can access controlled airspace through the current ATC system by communicating with an air traffic controller. As the number of ODM operations increases and current ATC become overburdened, a dynamic, fine-scale airspace allocation system utilizing DFRA may be implemented to relieve air traffic controller workload. Flight within the DFRA may first be managed simply through VFR self-separation with a dedicated communication network serving aircraft and UAS operating in the DFRA. However, as flight density continues to increase an electronic VFR system employing advanced technologies may be implemented to further reduce separation minima. At the extreme limit of flights densities, an airspace service provider could manage the DFRA providing network planning, 4D trajectory optimization and separation assurance.

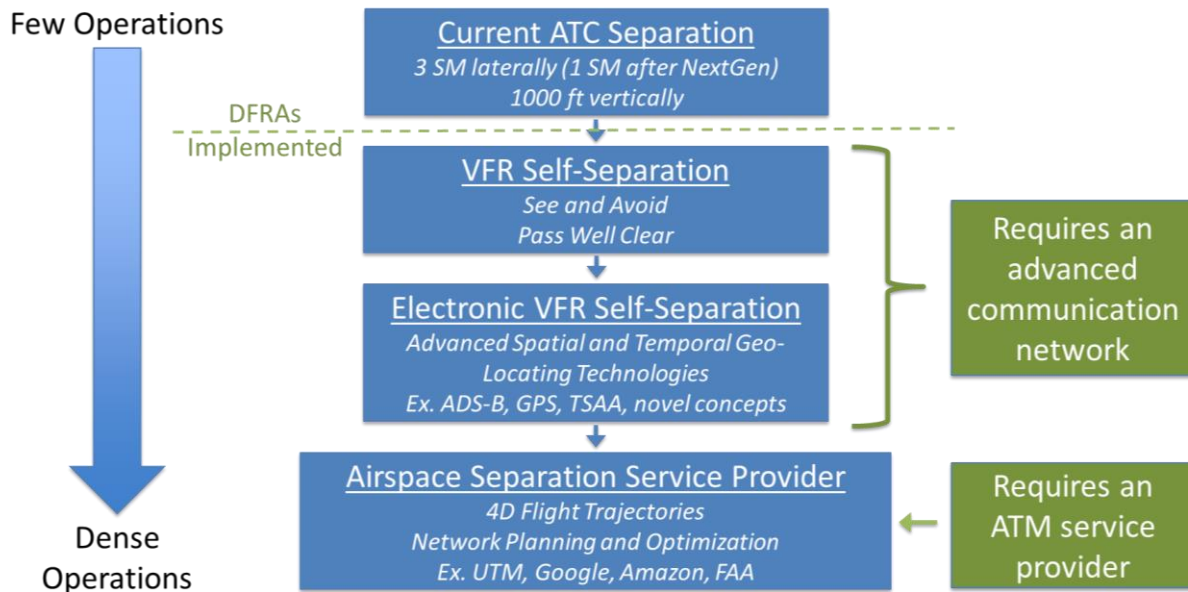


Figure 92. Notional ATM evolution displaying mitigation techniques to enable increasingly dense aircraft operations in low altitude, controlled airspaces while reducing air traffic controller workload and separation minima.

#### 7.2.4 Summary of Mitigation Potential to Scale ODM Networks under ATC

The review conducted in this section investigated four approaches for low altitude air traffic control developed by the UAS community. The review sought to assess if any of the approaches were adaptable as mitigation techniques to support ATC scalability for ODM Aviation operations. This review found that each of the four proposed techniques had the potential to support ODM operations in airspaces not controlled by ATC, however only one approach addressed operations within controlled airspaces. This approach, which involved expanding and modernizing the current ATC system, would likely only be available as a far-term solution due to the expense and duration of ATC modernization. Furthermore, none of the proposed mitigation techniques explicitly considered low altitude manned aviation, and a shift of focus would be necessary to develop these systems for both UAS and ODM aircraft.

Considering these limitations of the proposed mitigation approaches, the current-day utilization of airspace in proximity to the Los Angeles International Airport was reviewed using twelve months of ASDE-X flight trajectory tracking data. The review determined that over 80% of operations in the study were commercial flights that utilized only 5% of the available low altitude airspace. ATC, on the other hand, controlled 61% of the available airspace to support these operations.

The low utilization of airspace indicated that an opportunity existed to significantly increase flight density and ODM Aviation access to surface-level controlled airspaces through dynamic, fine-scale airspace allocation. The design and function of a notional dynamic, fine-scale airspace allocation system was demonstrated for the Bob Hope airport. It was found that while flight throughput in controlled airspaces was limited by air traffic controller workload and separation minima, this mitigation approach, when combined with advanced geo-locating and communications technologies, could improve low altitude ATC scalability.



### 7.3 Aircraft Noise

On Demand Mobility aircraft will operate closer to the public, in different areas, at different times of the day, and potentially more frequently than current aircraft operations. While aircraft overflight and VTOL operations near bystanders produce multiple potentially offensive impacts including vibrations, fumes, and blown debris, it is specifically the noise emissions from aircraft and helicopters that has historically been the most protested impact as evidenced by intense public awareness of aviation noise issues in many communities. As a result, aircraft noise is a significant constraint (perhaps the *most* significant near-term constraint) for ODM Aviation operations because public opinion can pressure regulatory authorities and government entities to limit or prohibit some aviation operations.

#### 7.3.1 Regulatory and Legal Pathways through which Aircraft Noise may Limit Operations

There are an abundance of examples where aircraft noise has prompted various stakeholders to limit or prohibit some or all aircraft and helicopter operations. In a particularly contentious public opinion example, noise generated by low flying helicopters in Los Angeles prompted California representatives to make numerous legislative attempts in Congress to instruct the FAA to create new regulations to reduce helicopter noise in the city. The effort ultimately resulted in the Los Angeles Residential Helicopter Noise Relief Act of 2013 [29]. The final version of the law did not strictly prohibit low altitude operations outright, but rather enabled the FAA to implement voluntary measures for Los Angeles operators to reduce noise [198].

Airports themselves have also frequently been the focus of aircraft noise debates. Within L.A., the Santa Monica Airport has been under pressure from the Santa Monica City Council and citizens for multiple decades due to the high volume of flights in and out of the airport in close proximity to the public [184]. These activists have reduced Santa Monica’s hours of operation, excluded some aircraft and operations all together, and are in a legal battle with the FAA to permanently shut down the airport (which the FAA recently agreed to allow in 2029). Table 50 displays a set of aircraft and helicopter operating restrictions for three major airports in Los Angeles that resulted from noise considerations.

Table 50. Aircraft and helicopter operational restrictions due to noise at major L.A. airports.

| Airport                         | Vehicle Type | Restriction  |
|---------------------------------|--------------|--|
| Los Angeles International (LAX) | Aircraft     | Westerly departure and arrival required between 2400 and 0630 hours                        |
|                                 | Helicopters  | All operations prohibited between 2200 and 0700  |
| Santa Monica (SMO)              | Aircraft     | No takeoffs between 2300 and 0700 hours  |
|                                 | Helicopters  | May not be used “as a base for any operation involving the substantial use of helicopters” |
| Van Nuys (VNY)                  | Aircraft     | No takeoffs between 2300 and 0700 hours if estimated noise level is >74 dBA                |
|                                 | Helicopters  | No restrictions  |

In a similar vein, the implementation of new, high-precision RNAV departure flight trajectories from Boston Logan Airport has substantially increased the frequency of which some landowners’

properties are overflowed and they experience increased noise. This has resulted in unprecedented public resistance to the implementation of the new ATM technology and led to attempted congressional and legal action to prohibit the implementation of RNAV routes at Logan airport [186], [187].

While a litany of additional examples could be presented, the key takeaway is that aircraft noise generation at low altitudes, especially during takeoff and landings, has frequently resulted in public action that imposed restrictions on the operations. Furthermore, it appears that there may be a changing basis of community noise acceptance; although some communities previously tolerated much more severe aircraft noise, current operations have reduced aircraft noise in the area and the communities will no longer tolerate a return to previous levels. This indicates that there is unlikely to exist a threshold dBA below which an aircraft will automatically be acceptable to communities.

Chapter 6 reviewed how nuisance, trespass, government takings and a variety of other *legal* mechanisms may potentially restrict low altitude flight due to noise concerns. Figure 93 displays the wide variety of *regulatory* pathways through which aircraft noise may result in operational restrictions. It should be noted that there are numerous stakeholders involved in this process, many of them elected officials or subordinate to elected officials, who have parallel pathways to impact aircraft operations. As a result, ODM Aviation may have to work with each of these stakeholders, or reduce the impact of aircraft noise on the public itself, in order to mitigate this constraint.

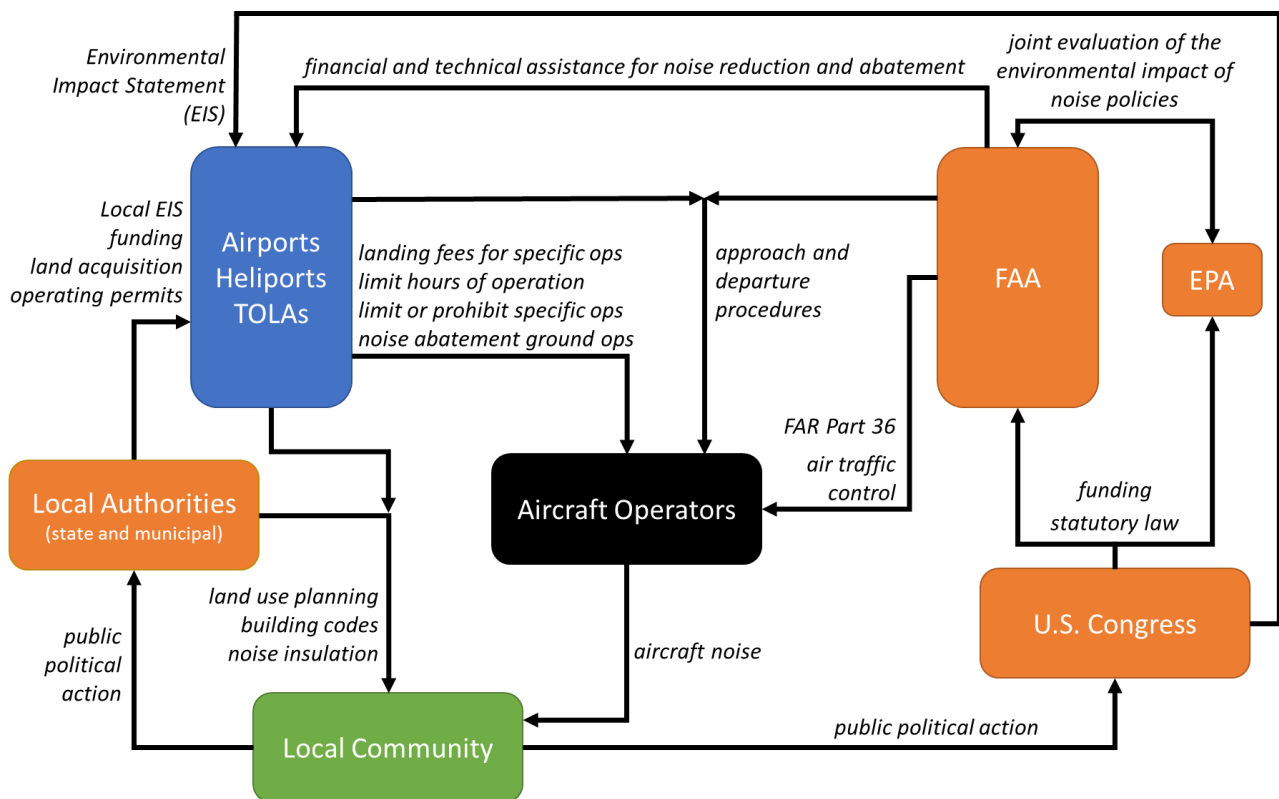


Figure 93. Regulatory pathways through which aircraft noise may result in operational restrictions for aircraft operators. Image developed from information in the FAA Airport Compliance Manual [199] and the 1976 Aviation Noise Abatement Policy III.3.a-e.

### 7.3.2 Current Approaches to Aviation Noise Mitigation

As a challenge in the aviation community that existed long before ODM Aviation, there are currently a variety of approaches to help mitigate aircraft noise. First, the FAA responds to noise complaints for aircraft or helicopter operations at low altitudes by assigning required flyways or routes, limiting airport hours of operation, or excluding some vehicles or operations all together from an area or airport [183].

Beyond noise generation regulations levied on the vehicles, voluntary or temporary noise reduction measures are common mechanisms employed to reduce the noise impacts of flight without the need for regulation. The FAA frequently creates Temporary Flight Restriction (TFR) areas around special public events (such as concerts or sporting events) that prohibit unauthorized low altitude flight in the area for noise reduction and safety purposes. The FAA has also created helicopter routes, airport transition routes, and VFR flyways that reduce the impact of aircraft noise by concentrating flights over less noise sensitive areas such as highways or industrial parks.

Furthermore, the FAA empowers airports to modify low altitude approach and departure paths for noise abatement purposes through the FAA Airport Noise Program, and asks pilots to adhere to low noise operational recommendations such as those outlined in the Helicopter Association International (HAI) *Fly Neighborly Guide* [200]. Finally, technological innovations in engine design, acoustic liners, airframe integration and numerous other components have steadily reduced the noise signatures of large aircraft [201].

### 7.3.3 Potential Noise Mitigation Opportunities for ODM Aviation

Aircraft noise is a complex specialty field of aviation with numerous areas of active research. The purpose of this section is not to delve into the detail of mechanisms to reduce bystander annoyance to aircraft generated noise, but rather to illuminate a few opportunities unique to ODM aircraft that show promise to achieve this goal.

The impact of aircraft noise can be mitigated through two fundamental approaches that may be generally considered as new technologies and noise reducing operations:

1. Technologies: Develop and implement new aircraft technologies that either reduce the source noise emissions from the vehicle, or reduce the annoyance of the noise generated to bystanders on the ground.
2. Operations: Operate the vehicle in a manner such that it either produces less total noise, or such that the noise is emitted in a location or way that causes less annoyance to bystanders on the ground.

A significant amount of interest and excitement has been expressed by the ODM community concerning the potential for new technologies incorporated in ODM aircraft to significantly reduce total noise emissions. The recent Uber white paper on ODM Aviation provides a significant amount of detail on various noise metrics for aviation, quantitative noise goals for ODM aircraft (expressed with these metrics), and the proposed technological means by which to reach them [2]. Table 51 displays a summary of the new technology-based mitigation proposals from this white paper as well as other authors.

Table 51. Technology-based ODM aircraft noise reduction proposals.

| Technology                     | Description   |
|--------------------------------|---|
| Electric Motors                | Replacing piston or turbine aircraft engines with electric motors removes significant mechanical, combustion and exhaust noise sources. Furthermore, electric motor power density is scale invariant, therefore 1-2 passenger aircraft may be developed with significantly reduced takeoff weight thereby reducing thrust and lift and drag requirements resulting in reduced noise generation.   |
| Distributed Propulsion         | Aircraft utilizing small, distributed electric propulsors are able to achieve comparative vehicle performance to helicopters while capturing a variety of acoustic benefits. The small propellers may be operated with slower tip speeds (reducing noise) and at higher RPM to avoid low-frequency noise generation. It should be noted that while high-frequency noise is rapidly attenuated by the atmosphere as compared to low-frequency noise, it is more disagreeable to bystanders at close range. Finally, some propellers may be de-powered (and potentially folded) during cruise to reduce noise generation. |
| Frequency Spectrum Spreading   | On-going research by NASA is investigating if operating distributed propulsors at slightly different speeds may spread the emitted frequency spectrum in a manner that reduces the perceive noise annoyance of bystanders.  |
| Tiltrotor, Fixed Wing Aircraft | Tiltrotor capabilities enable VTOL while avoiding edgewise flow over the rotors during forward flight (as the vehicle cruises in a fixed-wing configuration). This reduces required rotor speed and reduces noise. Cruise in a fixed-wing configuration also reduces thrust requirements compared to vertical lift configuration further lowering noise.  |

In addition to the potential benefits of these new technologies, performance characteristics unique to some of the new ODM aircraft designs may allow them to be operated in ways that also significantly reduce bystander noise exposure. For example, the HAI *Fly Neighborly Guide* recommends that helicopters utilize takeoff and descent profiles that are as steep as practicable in order to limit low overflight of neighboring properties and bystanders. While helicopters have typically avoided extended vertical (or extremely steep) ascent and descent profiles due to vortex ring state (settling with power) concerns and autorotation safety, new distributed electric propulsion ODM aircraft may be able to execute these maneuvers safely.

Table 52 displays a set of operations to reduce noise that are currently recommended for helicopters that new ODM aircraft and operators may be able to execute more effectively.

Table 52. Noise reduction operations enhanced by potential ODM aircraft capabilities.

| <b>Operation Attribute</b>       | <b>Description</b>  |
|----------------------------------|---|
| Cruise at Higher Altitude        | Due to their higher anticipated cruising velocity compared to helicopters, the relative velocity differential between ODM aircraft and fixed-wing aircraft operating at mid to high altitudes over metropolitan areas will be reduced. As a result, ODM aircraft may be approved by ATC to operate in higher altitude, controlled airspaces above many metropolitan regions reducing their ground noise signature. In contrast, the lower reaches of these airspaces are typically considered as maximum altitude ceilings for helicopter operations. |
| Extended VTOL Ascent and Descent | If ODM aircraft with DEP do not exhibit vortex ring state susceptibility during rapid descent, then these vehicles may be able to operate true vertical ascent and descent profiles reducing low altitude overflight near TOLAs.  |
| Avoid Impulsive Noise Generation | Tiltrotor ODM aircraft are likely to avoid impulsive noise generation (blade slap) during sharp maneuvers or high speed descent if they operate in a fixed-wing configuration for these mission segments.   |
| Avoid Noise-Sensitive Areas      | While many current helicopter charter flights operate for tourism purposes and frequent populated areas or iconic structures at low altitudes, ODM missions are generally for transportation and may be routed to avoid these areas.  |

#### ***7.4 Community Access to Takeoff and Landing Areas***

A majority of existing TOLAs were not designed for high throughput, public operations. These facilities often do not have public parking, drop-off and pickup locations, linkages to transit, quick and well indicated access or egress routes, or safety and security measures commensurate with public operation. While new infrastructure could readily be specifically developed to support ODM operations, existing helipad infrastructure, especially rooftop facilities, may not currently be well suited for such operations and could require significant retrofitting.

Unlike the three previous ODM Aviation constraints, providing safe and efficient community access to takeoff and landing areas has a variety of relatively straight forward potential mitigation opportunities. The primary challenges in implementing these mitigations are likely be cost and negotiations with private landowners.

Beginning with existing TOLA infrastructure considerations, Los Angeles currently has 310 improved landing facilities suitable for VTOL operations as outlined in Table 41. However, only 16 of these facilities (the airports) currently support extensive public operations. Much of the rest of the existing infrastructure, especially the emergency helicopter landing facilities, are unlikely to have the physical infrastructure to support public operations. Table 53 presents a description of some potential infrastructure that a TOLA may require to support public ODM operations. Please

note that every TOLA may not require all of these items, but they will be necessary on a case by case basis.

Table 53. Potential TOLA access and safety infrastructure requirements.

| <b>TOLA Access and Safety Infrastructure</b> | <b>Description</b>  |
|--|---|
| Public access and egress route               | TOLAs may require clearly indicated public access and egress routes. This may be especially challenging for rooftop TOLAs in private, secure buildings or airports where either an escort or private elevator/stairwell may be necessary. |
| Vehicle parking or drop-off point            | TOLAs may require a passenger drop-off area or transit connection. It may be beneficial for some TOLAs to have private vehicle parking options.   |
| Passenger staging area                       | A shelter may need to be provided at an appropriate distance from the takeoff and landing surface to provide passengers protection from downwash and the elements.  |
| Facility security                            | TOLAs are hazardous areas with heavy machinery. Security measures such as perimeter fences and lighting may be necessary to protect bystanders and prevent unauthorized access to the TOLA.   |
| Flight security check area                   | Although not currently required for aircraft under 12,500 lbs, future ODM operators could potentially be required to conduct a pre-flight security check.   |
| Check-in and customer identification area    | TOLAs may require an area to conduct customer check-in and identification. This process will likely be required to occur outside the secure TOLA area or private property.  |

Some existing TOLA infrastructure may require retrofitting with items from Table 53 before accommodating public ODM operations. Physical updates to existing TOLAs, especially at private facilities, are likely to require contractual agreements with the landowner. This could represent a significant legal expense and be a tedious exercise for ODM operators in the near term. Furthermore, while on-site staff may significantly reduce some of the community access and security challenges by identifying passengers, conducting necessary pre-flight activities (security and check-in), and escorting the passengers to the TOLA, the expense of supporting staff at a large network of TOLAs may be prohibitive.

Considering these factors, the ODM community has proposed some alternative approaches to mitigate community access concerns. One such proposal is to partner with a ridesharing service to provide customer transportation and access to TOLAs. Such a partnership could possibly eliminate the need for vehicle parking, enable customer check-in and a security check at an off-site location, and provide an escort to the TOLA. An alternative proposal is to task the pilot with exiting the aircraft to meet the customer and conduct these same pre-flight tasks. Both of these approaches remove the need for dedicated on-site staff, but add additional challenges in terms of training for pilots or drivers and may reduce throughput due to longer aircraft turn-times.

A second consideration beyond a customer's *physical* access to a TOLA is if customers have good *geographic* access to TOLAs. Considering this, the location of new TOLA infrastructure may be chosen to maximize community geographic access to the TOLAs. For near-term ODM Aviation network development, it may be prudent to co-locate new TOLA infrastructure with public transportation nodes and major roadway arteries. Intermodal access will enable the ODM network to provide service to a significant geographic area through a minimal number of TOLAs by leveraging the current ground transportation networks. As more TOLAs are added to the ODM network in the far-term, the need for tight intermodal integration of these ground transportation modes may be diminished.

Figure 94 presents four concepts or existing techniques to integrate TOLA facilities with ground transportation infrastructure. Sub-image (A) presents a concept from a recent NASA publication to co-locate new TOLA infrastructure inside the clover leaf interchanges of highway infrastructure. NASA notes that beneficial aspects of this scheme include easy access by automobile to major transportation arteries, masking of ODM aircraft noise within highway background sound levels, and existing government ownership of land at the TOLA site and under aircraft approach or departure trajectories. A concept such as this may enable single aircraft TOLAs to be tightly integrated with highway infrastructure, although concerns have been raised about the safety of low altitude flight and landings overtop highway infrastructure, and the practicality of using the TOLAs during high congestion periods (when ODM Aviation demand is likely to be highest) since access and egress to the TOLAs is restricted by the flow of traffic on the congested highways.

Sub-image (B) displays a concept from Uber Elevate that co-locates a high-capacity TOLA with a multi-level parking facility. This configuration provides additional benefits of private vehicle parking, a passenger staging area, staff, security and check-in equipment housing, and the potential to locate the facility in dense metropolitan areas.

Finally, sub-images (C) and (D) present two existing heliport facilities that are integrated with downtown city areas through city buses, highways and waterways. These facilities share the same benefits as the high-capacity TOLA in sub-image (B).

[Intentionally left blank]



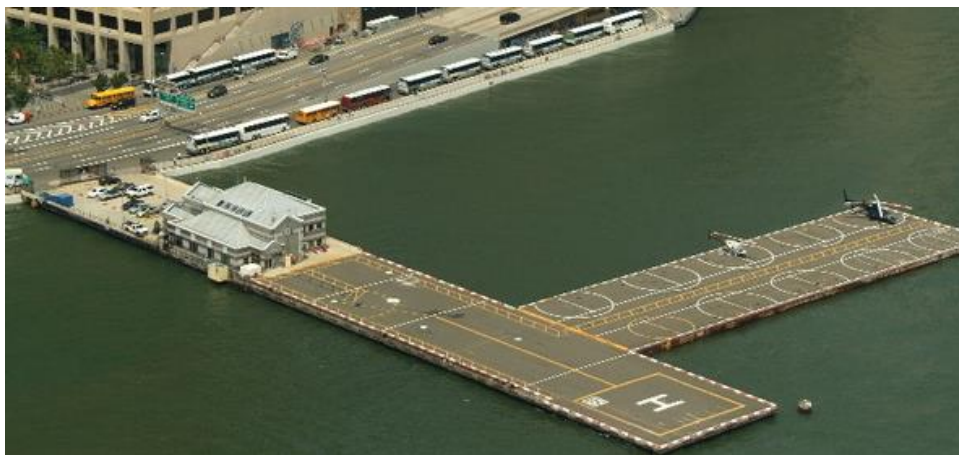
(A) – Highway clover-leaf TOLA  
*Image courtesy NASA [13]*



(B) – Parking garage rooftop TOLA  
*Image courtesy Uber Elevate [2]*



(C) – TOLA co-located with intra-city bus line  
*Image retrieved 7/10/2016 from [www.visitmonaco.com](http://www.visitmonaco.com)*



(D) – Pier TOLA co-located with highway and river access.  
*Image retrieved 8/15/2016 from [www.coreheli.com](http://www.coreheli.com)*

Figure 94. Concepts to integrate TOLAs with ground transportation infrastructure.



## ***7.5 Scalability of ODM Networks Operating Outside ATC***

If ODM operations increase the density of aircraft flights in airspaces unsupported by ATC well beyond what is experienced today, then the capacity of the current rules of the road may be insufficient to provide flight safety and efficiency. This challenge may be especially pronounced in special flight rules areas, dynamic flight rules areas, helicopter corridors and other standard exclusion routes where VFR traffic is naturally funneled into by airspace design. These “choke points” could limit throughput if a critical flight density is reached. Similar challenges could also be experienced near high-capacity TOLAs or high-demand pickup and drop-off locations.

It should be noted that aircraft operating outside the purview of ATC are not necessarily in uncontrolled airspaces. For example, while Class E airspace is a controlled airspace, flights operating with VFR may occur without ATC support. Similarly, many SFRAs pass inside of Class B or C airspaces but are excluded from ATC support.

Similar to the community access to TOLAs constraint, this constraint was anticipated to have a less severe impact upon near-term ODM Aviation operations. Furthermore, the ODM community has identified a number of potential technologies and approaches that may mitigate this constraint.

First, a variety of companies are developing less costly, lighter versions of ADS-B to support GA, UAS and new small aircraft markets such as ODM. Many metropolitan areas in the United States, including Los Angeles, are surrounded by a “Mode C veil” that extends horizontally to a radius of 30 nmi around the major Class B airport in the area. Beginning in 2020 all aircraft operating in the Mode C veil will be required to be equipped with ADS-B. The universal adoption of ADS-B in the metropolitan areas will improve flight safety and support more dense airspace operations in the very areas where ODM Aviation networks are likely to experience the most significant congestion.

The adoption of ADS-B may represent the beginning of a trend towards new aviation technologies that electronically enhance a pilot’s capability to operate in close proximity to other aircraft. The development and implementation of more advanced technologies such as Traffic Situation Awareness with Alerting (TSAA) may further increase the throughput of airspace without ATC [202]. Beyond these sensing and awareness technologies, non-ATC affiliated flight planning or tracking applications such as those in development and use by LATAS Air or FlightAware for UAS and manned aviation, respectively, may ultimately be expanded to provide local, regional or national trajectory planning and real-time flight tracking services with congestion notification to pilots.

Broadly, this class of advancements in technology and aircraft connectivity that enhance a pilot’s awareness and capacity to fly in more congested airspace may be referred to as electronic VFR, or eVFR operations. Such systems may be developed and implemented in the relatively near-term to steadily increase the throughput of flights through airspaces.

The next step beyond eVFR to further increase airspace throughput and flight density may be to adopt increasingly autonomous operation. The ODM Aviation community has focused in numerous workshops on the concept of developing automation to enable “simplified vehicle operations” to reduce piloting requirements and ultimately eliminate in-vehicle pilots all together. While full-automation is likely a far-term goal for ODM Aviation, the automation capabilities in

development may logically first find application during mission segments that pass through highly congested airspace corridors where the situational awareness capabilities of computers can more safely operate the aircraft in close proximity to many other vehicles.

Finally, as discussed in Section 7.2.3, at the extreme limit of flight density an airspace service provider could provide network planning, 4D trajectory optimization and separation assurance for congested airspaces not served by traditional ATC.

## 8 Conclusion

*To bring a technically sophisticated new transportation system into existence requires intelligent cooperation between manufacturers, operators, airport owners, and the public as represented by various agencies of federal and local government.*

- MIT Flight Transportation Laboratory [20, p. A-18]

### 8.1 Review of the Thesis Research Questions

This thesis developed and implemented a holistic, systems-level analysis approach to investigate the operational potential of ODM Aviation and answer the three research questions presented in Section 1.4. The three research questions are restated below along with a succinct review of the relevant findings and results developed through this thesis.

**RQ1 - CONSTRAINTS: What are the critical technological, operational, regulatory, business or system interface factors that may constrain or prevent ODM Aviation implementation in the United States?**

Five primary constraints were identified that may impact the development, implementation or operation of ODM Aviation networks in the near or far-term. These constraints were determined through a review of the concept of operations for twelve reference missions that serve promising ODM Aviation markets in the Los Angeles basin. Furthermore, a review of the legal and regulatory uncertainties concerning low altitude aircraft operations provided additional insight into constraints regarding infrastructure development and aircraft noise. Table 54 answers Research Question 1 by presenting the five ODM Aviation constraints and describing the key characteristics of each.

In addition to the five constraints reviewed in Table 54, this research also pin-pointed three additional issues that may negatively influence the implementation or operation of ODM Aviation networks. A challenge was considered an ODM Aviation issue rather than a constraint if there was a significant level of uncertainty surrounding how (or if) the challenge could limit ODM services. The three ODM Aviation issues are presented in Table 55 along with a description of the key characteristics of each.

An interesting finding of this thesis was that the severity of the identified constraints varied dramatically with the assumed *scale* of the ODM network. This indicated that while some constraints may not influence near-term ODM operations, they may become binding constraints for far-term services as more aircraft enter the network.

The findings of this thesis suggested that aircraft noise is likely to be the most severe near-term constraint for the implementation of ODM Aviation services in the United States. Although cities such as New York, San Francisco, Boston, and Los Angeles have relatively well-established helicopter charter services, the routes and areas served by these operators is largely limited by community noise factors. Furthermore, while these four cities previously had extensive helicopter transportation networks with similar qualities to the newly proposed ODM networks, the metropolitan regions have by and large become less tolerant of aircraft noise and would not accept the return of such services without significant noise reductions.

Table 54. ODM Aviation constraints.

| ODM Aviation Constraint |   | Key Constraint Characteristics  |
|-------------------------|---|---|
| 1                       | Availability of Takeoff and Landing Areas (TOLAs)           | <ul style="list-style-type: none"> <li>- The average distance from the origin to current aviation infrastructure in the reference missions was 3 miles</li> <li>- Some suburban regions were found not have existing aviation infrastructure within 10 miles</li> <li>- The lack of TOLAs amplifies aircraft staging, congestion and route capacity challenges</li> <li>- The development and use of new TOLA infrastructure is dependent upon approval from the municipal governments and landowners</li> <li>- TOLAs located in residential areas may expose operators to nuisance or government takings lawsuits from nearby landowners disturbed by the operations</li> </ul> |
| 2                       | Scalability of ODM Networks under Air Traffic Control (ATC) | <ul style="list-style-type: none"> <li>- Over 40% of urban and suburban Los Angeles resides within a surface-level controlled airspace</li> <li>- 92% of the reference missions required entrance into a surface-level controlled airspace</li> <li>- A high density of ODM Aviation operations may overload ATC capabilities, reduce or eliminate aircraft throughput, and create interaction issues with helicopters, aircraft and UAS in these airspaces</li> </ul>  |
| 3                       | Aircraft Noise  | <ul style="list-style-type: none"> <li>- TOLAs are likely to be located within urban and suburban areas bringing aircraft operations in closer proximity to people than current airports</li> <li>- Aircraft noise makes ODM operations susceptible to nuisance or government takings lawsuits</li> <li>- Aircraft noise may restrict access to TOLAs in specific geographic areas or during certain times of day</li> </ul>  |
| 4                       | Community access to TOLAs                                   | <ul style="list-style-type: none"> <li>- TOLAs must be readily accessible by the public and support inter-modal linkages to foster ODM demand</li> <li>- TOLAs are hazardous areas and appropriate safety and security must be provided</li> <li>- If TOLAs require on-site staff, the carrying cost of ground infrastructure is significantly increased</li> </ul>   |
| 5                       | Scalability of ODM Networks Operating Outside ATC           | <ul style="list-style-type: none"> <li>- Significantly increased flight densities may surpass the capacity for current rules of the road and self-separation approaches to ensure safety</li> <li>- The implementation of low altitude, 3<sup>rd</sup> party airspace management services for UAS may exclude or complicate ODM access to some airspaces</li> </ul>   |

Table 55. ODM Aviation issues.

| ODM Aviation Issue |  | Key Issues Characteristics   |
|--------------------|--|--|
| 1                  | Electric aircraft operating standards and certifications | <ul style="list-style-type: none"> <li>- There are no existing standards for minimum allowable takeoff energy (dispatch energy)</li> <li>- There are no existing electric aircraft airworthiness and pilot certifications</li> <li>- There are no existing standards for electric aircraft minimum energy reserve requirements</li> <li>- There are no existing standards for electric aircraft alternative safe landing location requirements</li> <li>- It is unclear whether distributed electric propulsion aircraft will require a multi-engine pilot rating</li> </ul> |
| 2                  | Weather conditions                                       | <ul style="list-style-type: none"> <li>- Cold temperatures may degrade electric aircraft battery performance</li> <li>- High winds may degrade network coverage or service</li> <li>- Reduced visibility and IFR flight may reduce network coverage or service</li> <li>- Frequent (especially unanticipated) reductions in coverage or service may degrade consumer demand</li> <li>- Precipitation, rough ride conditions, or hot/cold cabin conditions may reduce customer demand</li> </ul>  |
| 3                  | Interaction of ODM aircraft with UAS                     | <ul style="list-style-type: none"> <li>- How is priority established for vehicles desiring to operate in the same airspace?</li> <li>- How will ODM aircraft communicate with UAS?</li> <li>- How will ODM aircraft safety be assured during low altitude operations?</li> </ul>   |

The critical nature of the aircraft noise constraint for U.S. cities is made apparent when current-day helicopter operations in São Paulo are considered. By some estimates, there are over 400 helicopters traveling between a network of more than 250 helipads in the South American city [28]. The successful implementation of urban air mobility in São Paulo implies that many of the other constraints are not necessarily binding for the near-term implementation of ODM Aviation networks, but rather that the noise sensitivity of U.S. cities make aircraft noise a critical factor.

The second most critical near-term constraint was anticipated to be the availability of takeoff and landing infrastructure. While a limited set of high-capacity TOLA infrastructure in high-demand areas may support the near-term implementation of service along specific routes and corridors, a significant ground infrastructure development challenge (or vehicle performance design challenge) exists if the service is to become available for a broad geographic area. The lack of TOLA infrastructure amplifies aircraft staging, congestion and route capacity challenges.

Finally, the most significant constraint impacting the far-term scalability of ODM Aviation networks was anticipated to be air traffic control and airspace throughput (capacity) limitations. The current approach to ATC was hypothesized to be insufficient to handle a large volume of new ODM aircraft, especially if these aircraft operate in close proximity to one another in urban areas. Furthermore, it was identified that the proliferation of unmanned aircraft and the potential

development of new low altitude ATC approaches specifically for UAS may further complicate and constrain far-term ODM operations.

**RO2 - EXTERNALITIES: What externalities may originate from the proliferation of ODM Aviation networks in the United States, what potential impacts may they have on society, and how may they in turn influence ODM Aviation?**

This thesis introduced a variety of social equity and environmental justice externalities that could result from the implementation of ODM Aviation in metropolitan areas. The ODM Aviation community has an opportunity to consider these potential externalities, as well as others not identified or discussed in this thesis, during the conceptual design phase of this service and industry. Potential positive externalities may be maximized and leveraged to gain government funding, public acceptance, or market share. Negative externalities may be mitigated or internalized to avoid post-implementation issues such as litigation, regulation or reduced demand.

A full listing of the identified externalities and their associated impacts on ODM Aviation is provided in Appendix D, however a selection of the most promising opportunities and more pressing issues from the externality analysis are discussed in this conclusion.

First, ODM Aviation is a far more flexible form of transportation than current surface modes due to the nodal nature of the service and the small amount of built infrastructure required to support the service. ODM TOLAs may be constructed at relatively low cost and land footprint compared to roadways or railways. This quality may enable ODM Aviation networks to develop infrastructure in *transit deserts* and provide increased mobility to communities that are currently underserved by existing modes. ODM operators may potentially leverage this positive social equity externality in the near-term to garner public or private funding to develop infrastructure and provide services to these communities, for example.

Second, the nodal nature air transportation also makes it an ideal mode to serve polycentric city structures and support regional urbanization. As metropolitan areas continue to expand, secondary downtowns or satellite cities have developed on the periphery of central business districts. Los Angeles, for example, has 45 distinct urban employment centers. High-demand transportation corridors span between these business districts, but such surface corridors often experience severe congestion that limit the effective movement of people. ODM Aviation is well suited for these inter-city missions. The service may therefore support the growth of satellite cities and regional urbanization which is anticipated to bring about a variety of positive social, environmental and economic externalities. ODM Aviation operators may therefore be able to secure local city government support and funding to develop high-capacity downtown TOLA infrastructure and operate inter-city corridors.

Third, urban air mobility may result in intensified socio-economic segregation. If high-income individuals utilize ODM Aviation services to move to fly-in communities that are geographically and socially isolated from underprivileged communities, then a negative social equity externality may result. The impact on ODM operations from this externality may be operational limitations or taxes by city governments.

Finally, ODM Aviation may provide a variety of positive environmental justice externalities to regions where it is implemented. First, full-electric ODM aircraft will reduce the lifecycle environmental impacts of flight compared to helicopters currently providing intra-city charter flights. Secondly, ODM aircraft may be used to move customers along specific routes that have high surface congestion or circuitous ground paths and require environmentally high-impact ground transportation. In cases such as these, the ability of aircraft to fly over obstacles may not only significantly reduce the time to complete a journey compared to private cars, but also the total greenhouse gas emissions of the trip. By operating ODM aircraft along routes that maximize these positive environmental impacts, operators may potentially tap into the greenhouse gas reduction policies of many states to support near-term implementation.

**RQ3 - POTENTIAL MITIGATIONS: What technology or policy options may be considered in both the near and far-term to address the binding constraints or negative externalities of ODM Aviation implementation in the United States?**

Chapter 7 investigated a variety of mitigation proposals for each of the ODM Aviation constraints. Both the near-term and far-term efficacy of the mitigation approaches were considered. Implementation feasibility in terms of cost, community acceptance, technical feasibility and interaction with the current systems, among other factors, was also assessed. The purpose of Research Question 3 was not to propose actionable mitigation approaches for each identified constraint and externality. Rather, the aim of this research question was to compile a listing of proposed mitigation approaches, evaluate the potential of these approaches to address the identified challenges, and reveal challenges that were not sufficiently mitigated by the current proposals and represent areas requiring future investigation.

*Availability of Takeoff and Landing Areas*

Although there are numerous proposed mitigation techniques that show potential to increase the availability of TOLAs in a geographic area, the implementation of a majority of the techniques is hampered by aircraft performance, regulatory, community acceptance or business challenges. New technologies, especially electric aviation, show promise to reduce or overcome the aircraft performance and community acceptance challenges of developing new TOLAs. However, existing regulations by and large currently prevent aircraft from landing outside official TOLAs and require a relatively tedious process to approve the construction and use of a new facility.

TOLA availability represents a classic “chicken and egg” conundrum. ODM Aviation networks can only attract and serve a large base of customers once a geographically distributed set of TOLAs is implemented with sufficient capacity. However, the financing and market acceptance required to develop a geographically distributed set of TOLAs may only emerge once the benefits of ODM Aviation are widely acknowledged through the successful implementation of these services.

Recognizing this challenge, ODM operators may benefit from beginning services with limited ground infrastructure along specific routes or corridors to gain experience and build positive public sentiment. Additionally, investors or businesses with geographically diverse storefronts may capture entire new markets by investing in TOLA development and certification in the near-term in order to lease access to the emerging ODM operators in the far-term.

### Scalability of ODM Networks under Air Traffic Control

This thesis sought to identify approaches that would enable the increased throughput of ODM aircraft, UAS and other vehicles in controlled airspaces, especially at low altitudes. Four low altitude air traffic control schemes developed for the emerging UAS industry were initially reviewed. It was found, however, that none of these approaches sufficiently met the needs of ODM Aviation networks. Primary issues with these approaches included the focus of these new systems on UAS operations, the inefficient use of airspace through geofencing and attitude stratification, a lack of coordination with current ATC, or an unacceptably long anticipated development and implementation period.

Considering these limitations of the proposed mitigation approaches, the current-day utilization of airspace in proximity to the Los Angeles International Airport was reviewed using twelve months of ASDE-X flight trajectory tracking data. The review found that over 80% of operations in the study were commercial flights that utilized only 5% of the available low altitude airspace. ATC, on the other hand, controlled 61% of the available airspace to support these operations.

The low utilization of airspace indicated that an opportunity existed to significantly increase flight density and ODM Aviation access to surface-level controlled airspaces through dynamic, fine-scale airspace allocation. The design and function of such an airspace allocation system was demonstrated for the Bob Hope airport. It was found that while flight throughput in controlled airspaces was limited by air traffic controller workload and separation minima, dynamic, fine-scale airspace allocation combined with advanced geo-locating and communications technologies could improve low altitude ATC scalability. Figure 95 displays a suite of technologies and systems that could potentially be used to systematically increase the throughput of aircraft through controlled airspaces.

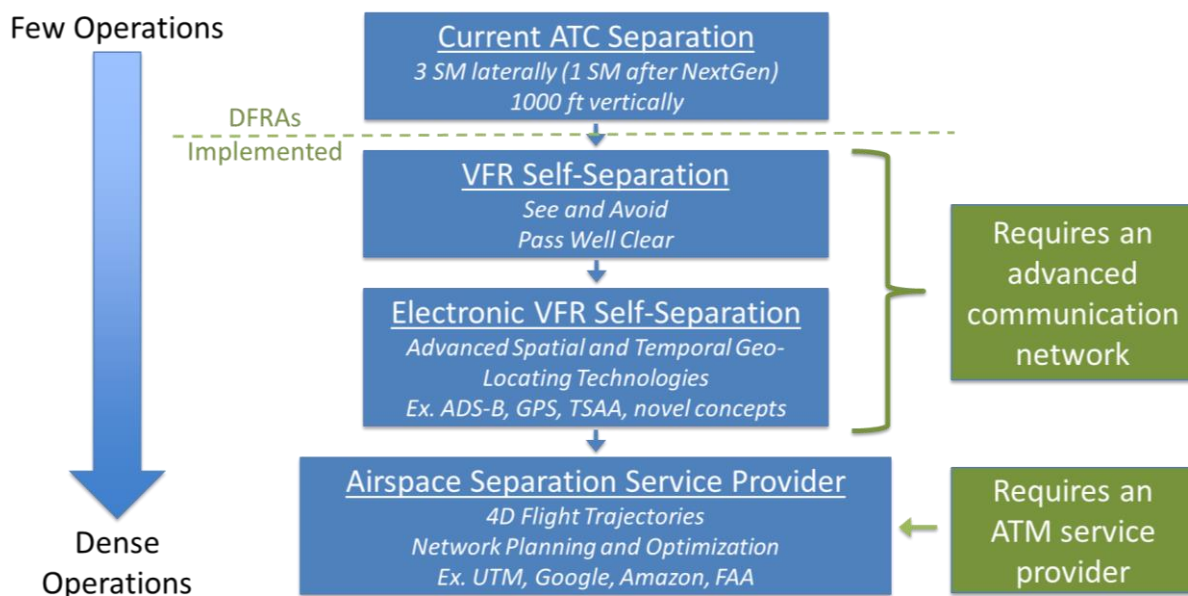


Figure 95. Notional ATM evolution displaying mitigation techniques that enable increasingly dense aircraft operations in low altitude, controlled airspaces while reducing air traffic controller workload and separation minima.



### Aircraft Noise

Aircraft noise was determined to be perhaps the *most* significant near-term constraint for ODM Aviation operations. Noise emissions from aircraft and helicopters have historically been the most protested community impact of airports. Such public action has frequently placed pressure on regulatory authorities and government entities to limit or prohibit some aviation operations. As a result, aircraft noise from ODM aircraft was anticipated to indirectly influence the location and operation of TOLAs, the type of aircraft that may be used, and the market demand for ODM Aviation services.

Two categories of potential noise mitigation techniques were explored in this thesis. First, *technology-based* mitigations including electric motors, distributed propulsion, frequency spectrum spreading and tiltrotor configurations were reviewed. These technologies were found to represent a noise reduction potential over current helicopters. Furthermore, these technologies increased the effectiveness of the second category of noise reduction techniques referred to as *operational-based* mitigations. Due to unique aircraft performance capabilities, new ODM aircraft may be able to fly at higher cruise altitudes, conduct extended vertical ascents and descents into and out of TOLAs, avoid impulsive noise generation, and bypass noise sensitive communities. These operational-based mitigation techniques have the potential to further reduce the impact of aircraft noise to bystanders on the ground.

### Community Access to Takeoff and Landing Areas

This thesis reviewed how the public's *physical* and *geographic* access to TOLAs may influence the operation of an ODM Aviation network. Preliminary findings suggested that security, insurance and passenger handling requirements likely necessitate that on-site staff to be located at each TOLA. Such staff represent a significant carrying cost for the network and indicate that the development of fewer, high-capacity TOLAs to support near-term ODM operations may be a cost minimizing development strategy.

The downside to this near-term approach, however, is that while a network with fewer TOLA's minimizes operational costs, it also reduces the geographic region with access of the ODM network and reduces the share of the transportation market that may be captured. Further findings indicated that co-locating TOLAs with surface transportation hubs (such as subway stops, bus depots or train stations) may leverage the geographic coverage of those networks to feed into the ODM Aviation system and address this near-term challenge.

Overall, the community access to TOLAs constraint was perceived as less impactful than a majority of the other constraints. Available mitigation approaches also appeared sufficient to address the limitations imposed by this constraint.

### Scalability of ODM Networks Operating Outside ATC

ODM networks that operate in airspaces that do not provide ATC services will benefit in the near-term by avoiding capacity restrictions due to air traffic controller workload. However, far-term operations in these airspaces may experience throughput constraints and safety concerns as the flight densities of aircraft overwhelm VFR self-separation capabilities.

Potential approaches to support high density aircraft operations were introduced in the investigation of the dynamic, fine-scale airspace allocation system proposed for controlled airspaces. Therefore, this research suggested that the electronic VFR, self-separation, and airspace separation service provider mitigation approaches proposed in Figure 95 were also valid mitigation approaches to support the scaling of aircraft operations in regions without current ATC services.

### Externalities

Specific mitigation approaches were not assessed for each of the identified negative externalities. However, the following general approaches showed promise to address many of the operational impacts that may occur in response to the externalities.

1. Avoid operations or missions that uniquely exacerbate a negative externality. This could be accomplished by requiring commuter trips have two or more passengers, or not offering flights for routes well served by public transit options, for example.
2. Internalize the cost of the negative externality. This could be accomplished by purchasing aviation easements over property near TOLAs, subsidizing trips in low-income areas through increased fares in high-income areas, or by offering career retraining for individuals put out of a job by ODM Aviation, for example.
3. Engage local stakeholders and impacted communities. If an externality cannot be avoided or internalized, then ODM Aviation operators may potentially avoid reactive operational burdens by engaging the local governments and impacted communities to build community support for the benefits of ODM Aviation and jointly address the challenges.

## **8.2 Additional Contributions**

As presented through the review of the research questions, the primary takeaway from this thesis is that ODM Aviation stands to bring about a step-change in mobility and a host of economic and quality of living benefits for society, but must first address five constraints, three issues and a variety of potential externalities.

In addition to those primary findings, the research presented in this thesis also provided a variety of additional contributions to the engineering, transportation and aviation communities. Each of these contributions is discussed briefly below.

### **1. An early-phase, systems-level analysis approach to conceptual design**

The systems-level analysis approach developed in this thesis and presented in Figure 2 is a contribution to the conceptual design and requirements engineering literature. Due to its reliance on first principles (rather than assumptions), the analysis approach is well suited for situations where little information is known about the technical and performance specifications of the system or operation.

With minimal assumptions the approach in this thesis identified likely high-value early adopter markets, created a set of representative reference missions, and developed a concept of operations that meets the requirements of the missions. Then, similar to approaches used in the soft systems, participative design and enterprise architecting communities, the approach evaluated each

reference mission through a variety of design perspectives to identify constraints and externalities. These design perspectives included regulatory, legal, environmental, technical and social viewpoints.

The analysis approach developed in this research has the distinct advantage of more completely reviewing the set of factors that may impact the development, implementation and demand for a new system. A purely technical or business analysis would not have the breadth and holistic nature necessary to capture constraints that emerge from system interfaces with other domains. Although the analysis approach does not delve into sufficient detail in any one domain to support detailed design, it provides conceptual designers with a wider net through which to identify challenges and address them preemptively.

Finally, beyond the conceptual design of ODM Aviation networks, the systems-level analysis approach developed in this thesis is also useful as a tool for market analysis. The reference mission definition process identified promising early adopting markets and even specific high-volume routes that represent potential near-term service opportunities. This process may be repeated in other cities to support the initial implementation of ODM Aviation services.

## **2. Recognizing the dynamic nature of constraints**

Through the constraint identification phase of this research it became apparent that the severity of operational constraints for ODM Aviation *change* over time in response to the scale of the ODM network. This realization led to the development of Figure 64 as an attempt to visually qualify and communicate to decision makers how the relative severity of constraints may vary.

Recognizing the dynamic nature of constraints during conceptual design is critical in order to support the planning of mitigations and services. Although significant future research is required on this topic, the author imagines that the “binding” constraint that limits ODM network size (for a specific area) could be forecast a priori through simulation and analysis. If this were the case, then business operators would know roughly when (in terms of network scale) the ground infrastructure constraint would dominate the noise constraint and become the barrier to further growth, for example. Such knowledge would enable program managers to optimize their R&D investment portfolio to deliver mitigation technologies or approaches for a specific constraint at roughly the same time it begins to bind further growth in the network.

## **3. Proposal of a *continuum of acceptability* for low altitude aircraft operations**

A final potentially significant contribution of this thesis is in the area of aviation law and regulation. The review of low altitude aviation determined that a private airspace demarcation altitude is essential to determine where aircraft may and may not operate from a trespass standpoint. However, this thesis proposed that above this demarcation altitude there exists a *continuum of acceptability* where flights may trigger nuisance or government takings litigation as a function of their *disturbance footprint* (which characterizes their noise, light, vibrations, viewshed disturbance, fumes, fuel particles and tactile impacts) and overflight altitude.

The consideration of a continuum of operational acceptability implies that smaller, less impactful vehicles may be permitted to operate at the private airspace demarcation threshold altitude while larger, high impact vehicles will be relegated to greater altitudes except during takeoff and landing.

The primary advantage of a legal (and regulatory) approach that embraces this concept is that instead of limiting all aircraft to operational altitudes deemed acceptable for the average or worst-case disturbance footprint, the standard is flexible and allows less impactful vehicles to operate in closer proximity to the population.

### ***8.3 Limitations of Study and Future Work***

The concept of urban air mobility is in its infancy. As a result, there is significant uncertainty concerning vehicle performance capabilities, markets, infrastructure requirements, regulatory acceptance, and demand, among other factors. Recognizing this, the approach taken in this thesis was to derive as much information as possible from first principles, remain performance and technology agnostic where possible, and draw results and conclusions based upon general trends rather than attempting specific, assumption-laden simulations and analyses.

While this first principles, holistic approach by and large avoided the need for qualifying assumptions, a variety of limitations must still be acknowledged concerning the research and case study conducted. However, these limitations are useful to suggest numerous areas ripe for future work. The most significant limitations of this research and proposed areas of future research are listed below:

#### **1. Conclusions were drawn upon results from the analysis of a single metropolitan area**

Perhaps the most significant limitation of the conclusions of this analyses is that they drew only upon results from the single case study in Los Angeles. As such, the constraints and issues identified for ODM Aviation are only fully valid for Los Angeles. Through intuition it is apparent that many of the constraints (such as aircraft noise) will also be applicable to ODM operations in other cities, however the severity of any particular constraint is likely change between cities.

Furthermore, it is also possible that a constraint or issue may exist for other cities that was not present in Los Angeles. An example of such a constraint would be weather. Weather may impact ODM operations in Los Angeles for less than 20 days per year, however inclement weather in Seattle or Chicago is far more common and severe and may place additional limitations on ODM operations that were not anticipated for Los Angeles.

Considering this limitation of the current research, a high priority area of future work is to apply the analysis approach developed in this thesis to a variety of other United States and international cities. Furthermore, cities with dramatically different geographic and societal characteristics should be evaluated to identify how ODM Aviation constraints vary in severity in response to the variance in these characteristics.

The ultimate outcome of this line of questioning would be to create a set of “leading indicators” that describes the characteristics of a city that most impact the ease of implementation of ODM Aviation services. Table 56 provides a notional leading indicators analysis based upon the results from Los Angeles and the intuition of the author.

Table 56. Notional leading indicators analysis for ODM Aviation implementation.

| <b>City Characteristic</b>            | <b>Description</b>  |
|---------------------------------------|---|
| City Structure                        | Polycentric cities or cities with sprawling suburbs may be more likely to adopt ODM Aviation  |
| Current Transportation Infrastructure | Cities with efficient, uncongested public transit options and roadways may be less likely to adopt ODM Aviation   |
| Geographic Obstructions               | Areas with geographic obstructions to surface travel such as bodies of water, mountains, parklands, slums, or political boundaries may be more likely to adopt ODM Aviation |
| Wealth                                | Regions containing a populace with relatively high average wealth may be more likely to adopt ODM Aviation  |
| Weather                               | Regions without severe weather and a significant number of low visibility days may be more likely to adopt ODM Aviation   |
| Available TOLA Infrastructure         | Areas with significant, pre-existing TOLA infrastructure may be more likely to adopt ODM Aviation   |
| Type of Government                    | Cities with strong central governments may be more likely to adopt ODM Aviation   |

## **2. Mitigation refinement and validation requires analyses at a level of detail beyond the capacity of this approach**

While the holistic approach adopted in this research was appropriate to identify the primary constraints for ODM Aviation during early-phase conceptual design, the level of detail of the mitigation analysis was insufficient to determine more than the general efficacy potential of these proposals.

Therefore, future work is in order to conduct a more detailed analysis for each constraint and the potential mitigation approaches or technologies proposed for that constraint. For example, a network simulation of all aircraft, TOLAs and consumer demand may be necessary to answer detailed questions about the environmental sustainability, economics and load balancing of ODM Aviation operations. Furthermore, detailed simulation of aircraft nose creation and ground impacts is another necessary area of research.

## **3. The system boundary of this analysis did not internalize interactions with other transportation modes**

The case study presented in this thesis did not directly consider the interfaces between ODM Aviation and other forms of mobility. These interfaces may be economic (percent of the market served by each mode), physical (inter-modal links), or strategic (transportation resiliency through dual-coverage of an area), for example. Other than hypothesizing about the relations between modes in some mitigation proposals and the externality analyses, these interfaces were not directly modeled or rigorously considered in this thesis.

Future research should expand the system boundary of this analysis to consider the entire transportation network contained within a metropolitan region. This line of research may be thought of as viewing a city's transportation system from a portfolio perspective. The flow of people in the network and their preference for one mode choice over the other (or intermodal trips) may readily be considered. Furthermore, the overall attributes of the city's *mobility portfolio* could

be tuned through investments in specific infrastructure, vehicles and routes, for example. Such an analysis (likely through simulation) may make it possible to draw conclusions about the percent of population that should be moved by each available mobility mode to maximize the overall resiliency, efficiency or any other quality of the transportation network.

#### **4. Insufficient far-term analysis**

Although this thesis was relatively thorough in its analysis of the near-term opportunities and constraints for ODM Aviation in Los Angeles, the far-term analysis was less complete. Far-term analysis is significantly more complex and requires the evaluation of multiple different future scenarios, as well as the path dependent development that led to those scenarios.

An intriguing area of future research would be to enhance the far-term analysis of ODM Aviation networks to better understand how investments and operational decisions in the near-term may impact the network scale, efficiency and demand for operations in the far-term. *Epoch-Era Analysis (EEA)* may be an effective mechanism to handle the complexity of this type of analysis. Furthermore, the use of EEA to conduct design tradeoffs for a portfolio of systems (such as a city's mobility portfolio) or for a transportation network have both been displayed in the literature [104], [105].

#### **5. The system boundary of this analysis was limited to metropolitan regions**

The analysis of ODM Aviation conducted in this thesis was limited to metropolitan regions. While densely populated areas certainly represent the largest foci of potential demand, it may be possible that rural areas represent viable near-term markets for ODM aircraft technologies that avoid some of the near-term constraints present for urban implementation.

Although the demand density in rural areas is unlikely to support true “on-demand” services, the relatively long distances, limited surface transportation options, reduced regulatory and local government issues, and wide availability of space for temporary TOLAs all indicate ODM Aviation may be well suited for these areas. The potential for ODM Aviation may be especially pronounced in communities that currently have limited surface transportation accessibility such as in developing regions of the world or high-latitude/elevation communities that experience seasonal access to roads.

#### **6. Travel time profiles and laborshed mapping was based on aggregate data**

The travel time profiles developed in this thesis were based upon route and congestion predictions from the Google Maps™ mapping service. While the Google travel time and congestion predictions are calculated from a wealth of travel data and other relevant information, they only provided aggregated, average travel times. However, many potential early-adopting ODM Aviation missions may serve large events such as baseball games or concerts. These events create one-time influxes in congestion that are not captured by the Google Maps™ mapping service. As a result, the travel time predictions for these scenarios may be underestimated.

Similarly, the U.S. Census data employed in this thesis to develop the laborshed maps aggregated individuals by census tract. A census tract typically contains between 1200 and 8000 people. However, depending upon the population density a census tract may contain only a few to thousands of acres. As a result, the geographic specificity of the laborshed maps may not be

sufficient to support the simulation of actual demand patterns and identify high priority locations for new TOLA development.

To address both of these limitations, future work may seek to utilize GPS tracking data from consumers' cell phones or car navigational units. A variety of scholars have displayed the usefulness of this data to assess mobility patterns with far more precise geographic and temporal resolution [150].

#### ***8.4 Final Thoughts***

On demand mobility for aviation, or more generally urban air mobility, stands to break the status quo of transportation and provide new mobility capabilities. ODM Aviation may enable cities and metropolitan regions to become more environmentally sustainable, equitable and economically productive. Individuals may have access to a greater freedom of movement than at any point in history, and they will no longer be tied to living in the communities in which they work. Urban planners, who have long been burdened by the limitations of linear surface infrastructure, may be able to leverage the nodal infrastructure of urban air mobility to overcome limitations of ground transport networks without requiring significant land use change in cities. Finally, ODM Aviation may become a central pillar of future *smart* cities.

However, although ODM Aviation represents incredible opportunities to change city structure and human mobility patterns for the better, if it were to be implemented haphazardly without diligent and intentional planning it could also result in numerous negative externalities. ODM Aviation may disrupt the equilibrium between city size and surface congestion enabling unbridled geographic growth and dramatic suburbanization. This would exacerbate societal challenges such as environmental sustainability and socio-economic equality. High-density networks of aircraft operating at low altitudes may also increase noise, reduce privacy and create new hazards over cities. Finally, as expressed in the quote below concerning autonomous cars, the rushed implementation of ODM Aviation operations by any one operator could potentially create significant public perception challenges for the rest of the industry to later overcome.

*Novel technologies depend on positive word of mouth to build consumer acceptance, but the opposite can happen as well. If there are terrible [autonomous] car crashes attributed to this technology, and regulators crack down, then certainly that would moderate people's enthusiasm. - MIT Technology Review [87, p. 39]*

Faced with these opportunities and risks, the ODM Aviation community is currently positioned within a unique "window of opportunity" from which it may influence the path this industry will take. The decisions and investments made in the next few years will form the foundations of the new industry and are likely to persist for decades as a result of technological, infrastructure and regulatory "lock-in." Through systems-level analysis and conceptual design, such as presented in this thesis, pathfinders in the ODM Aviation industry may make appropriate decisions today to reduce or avoid future challenges.





## 9 References

- [1] M. D. Moore and W. J. Fredericks, “Misconceptions of Electric Aircraft and their Emerging Aviation Markets,” in *52nd Aerospace Sciences Meeting*, 2014, no. January, pp. 1–17.
- [2] J. Holden and N. Goel, “Fast-Forwarding to a Future of On-Demand Urban Air Transportation,” San Francisco, CA, 2016.
- [3] V. Krishnamurthy, “Driven to Congestion: How the Planning, Engineering and Politics of Transportation Established, Preserves and Perpetuates the Automobile City,” Massachusetts Institute of Technology, 2007.
- [4] B. D. Bowen and F. D. Hansen, “Implementing a National Small Aircraft Transportation System: A Public Infrastructure Challenge,” *Public Work. Manag. Policy*, vol. 5, no. 2, pp. 160–169, 2000.
- [5] O. De Weck, D. Roos, and C. L. Magee, *Engineering Systems: Meeting Human Needs in a Complex Technological World*. Cambridge, MA: MIT Press, 2011.
- [6] S. Candel, “Concorde and the Future of Supersonic Transport,” *J. Propuls. Power*, vol. 20, no. 1, pp. 59–68, 2004.
- [7] L. R. Benson, *Quieting the Boom*. Washington, DC: NASA, 2013.
- [8] P. D. Vascik and J. Jung, “Assessing the Impact of Operational Constraints on the Near-Term Unmanned Aircraft System Traffic Management Supported Market,” in *16th AIAA Aviation Technology, Integration, and Operations Conference*, 2016, pp. 1–17.
- [9] M. Castells, “The Information Technology Revolution,” in *The Rise of the Network Society*, 2nd ed., Oxford: Wiley-Blackwell, 2009, pp. 32–33.
- [10] Y. Gawdiak, B. J. Holmes, B. K. Sawhill, J. Herriot, D. Ballard, J. Eckhaus, D. Long, R. Hemm, J. Creedon, C. Murphy, T. Thompson, F. Wieland, M. Marcolini, M. Moore, and M. Alcabin, “Air Transportation Strategic Trade Space Modeling and Assessment Through Analysis of On-Demand Air Mobility with Electric Aircraft,” in *12th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference*, 2012, no. September.
- [11] J. C. Smith, J. K. Viken, N. M. Guerreiro, S. M. Dollyhigh, J. W. Fenbert, C. L. Hartman, T.-S. Kwa, and M. D. Moore, “Projected demand and potential impacts to the National Airspace System of autonomous, electric, on-demand small aircraft,” in *12th AIAA Aviation Technology, Integration and Operations (ATIO) Conference and 14th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference*, 2012.
- [12] M. D. Moore, “Concept of Operations for Highly Autonomous Electric Zip Aviation,” in *12th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference*, 2012, no. September, pp. 1–15.
- [13] K. R. Antcliff, M. D. Moore, and K. H. Goodrich, “Silicon Valley as an Early Adopter for On-Demand Civil VTOL Operations,” *16th AIAA Aviat. Technol. Integr. Oper. Conf.*, no. June, pp. 1–17, 2016.
- [14] D. J. Nightingale and D. H. Rhodes, *Architecting the Future Enterprise*. Cambridge, MA: MIT Press, 2015.
- [15] W. L. C. Wheaton, “Form and Structure of the Metropolitan Area,” in *American Institute of Planners Conference*, 1966.
- [16] Flight 2014, “The Story of the World’s First Airline,” 2014. [Online]. Available: <http://www.airlinecentennial.org>. [Accessed: 01-Jan-2016].
- [17] ICAO, “Annual Report of the Council: The World of Air Transport in 2015,” Montreal, Canada, 2015.

- [18] A. C. Clarke, "Rescue Party," *ASTOUNDING Science Fiction*, pp. 36–60, May-1946.
- [19] J. S. Dajani, D. Warner, D. Epstein, and J. O'Brien, "The Role of the Helicopter in Transportation," Durham, N.C., 1976.
- [20] MIT Flight Transportation Laboratory, "Concept Studies for Future Intracity Air Transportation Systems," Cambridge, MA, 1970.
- [21] The Bowery Boys, "The Pan Am Building," *New York City History*, 2008. [Online]. Available: <http://www.boweryboyshistory.com/2008/09/podcast-pan-am-building.html>. [Accessed: 01-Jan-2016].
- [22] G. A. Gilbert, *Air Traffic Control: The Uncrowded Sky*. Washington, DC: Smithsonian Institution Press, 1973.
- [23] M. C. Branch, *Urban Air Traffic and City Planning: Case Study of Los Angeles County*. New York, NY: Praeger Publishers, 1973.
- [24] W. Saxon, "Copter Pad Born in Controversy," *The New York Times*, New York, p. 20, 17-May-1977.
- [25] R. D. McFadden, "5 Killed as Copter on Pan Am Building Throws Rotor Blade," *The New York Times*, New York, NY, p. 1, 17-May-1977.
- [26] A. Benepe and M. Birnbaum, "Attack of the Helicopters," *The New York Times*, New York, NY, p. SR, 31-Jan-2016.
- [27] T. Phillips, "High Above Sao Paulo's Choked Streets, the Rich Cruise a New Highway," *The Guardian*, 2008. [Online]. Available: <https://www.theguardian.com/world/2008/jun/20/brazil>. [Accessed: 01-Jan-2016].
- [28] K. J. Harrison, "Demand for Helicopters Rising in Latin America," *AIN Online*, 2013. [Online]. Available: <http://www.ainonline.com/aviation-news/business-aviation/2013-08-12/demand-helicopters-rising-latin-america>. [Accessed: 01-Jan-2016].
- [29] A. B. Schiff, *H.R.456 - Los Angeles Residential Helicopter Noise Relief Act of 2013*. U.S. Congress, 2013.
- [30] Federal Aviation Administration, "Los Angeles Helicopter Noise Initiative," Washington, DC, 2013.
- [31] R. W. Moorman, "Noise in the Cities - Revisited," *Vertiflite*, pp. 20–24, 2016.
- [32] NYCEDC, "NYCEDC and Helicopter Tourism & Jobs Council Announce New Measures to Reduce Helicopter Noise and Impacts Across New York City," 2016. [Online]. Available: <http://www.nycedc.com>. [Accessed: 01-Jan-2016].
- [33] Federal Aviation Administration, "AC 150/5390-3: Vertiport Design," Department of Transportation, Washington, DC, 1991.
- [34] F. Colucci, "Tackling Technical Barriers," *Vertiflite*, pp. 32–36, 2016.
- [35] D. Wolf, "On-Demand Mobility and Follow Up Workshop: Commuter Airline Perspective." Cape Air, Arlington, VA, 2016.
- [36] D. Espinoza, R. Garcia, M. Goycoolea, G. L. Nemhauser, and M. W. P. Savelsbergh, "Per-Seat, On-Demand Air Transportation Part I: Problem Description and an Integer Multicommodity Flow Model," *Transp. Sci.*, vol. 42, no. 3, pp. 263–278, 2008.

- [37] A. A. Trani, H. Baik, N. Hinze, S. Ashiabor, J. K. Viken, and S. Dollyhigh, "Nationwide Impacts of Very Light Jet Traffic in the Future Next Generation Air Transportation System (NGATS)," in *6th AIAA Aviation Technology, Integration and Operations Conference (ATIO)*, 2006.
- [38] M. D. Moore, "NASA Personal Air Transportation Technologies," *SAE Trans. J. Aerosp.*, vol. 115, no. 1, pp. 776–790, 2006.
- [39] Centre for Economics and Business Research, "The Future Economic and Environmental Costs of Gridlock in 2030," London, 2014.
- [40] Navigant Consulting, "Carsharing Programs," 2015. [Online]. Available: <http://www.navigantresearch.com/research/carsharing-programs>.
- [41] D. King, M. Manville, and D. Shoup, "The political calculus of congestion pricing," *Transp. Policy*, vol. 14, no. 2, pp. 111–123, 2007.
- [42] K. Carlin, B. Rader, and G. Rucks, "INTEROPERABLE TRANSIT DATA: Enabling a shift to mobility as a service," 2015.
- [43] M. Čertický, M. Jakob, and R. Píbil, "Analyzing On-demand Mobility Services by Agent-based Simulation," *J. Ubiquitous Syst. Pervasive Networks*, vol. 6, no. 1, pp. 17–26, 2015.
- [44] P. Santi, G. Resta, M. Szell, S. Sobolevsky, S. H. Strogatz, and C. Ratti, "Quantifying the benefits of vehicle pooling with shareability networks.," *Proc. Natl. Acad. Sci. U. S. A.*, vol. 111, no. 37, pp. 13290–4, 2014.
- [45] S. L. Smith, M. Pavone, M. Schwager, E. Frazzoli, and D. Rus, "Rebalancing the Rebalancers: Optimally Routing Vehicles and Drivers in Mobility-on-Demand Systems," in *American Control Conference (ACC)*, 2013, pp. 2362–2367.
- [46] F. Acquaviva, D. Di Paola, and A. Rizzo, "A Novel Formulation for the Distributed Solution of Load Balancing Problems in Mobility On-Demand Systems," in *International Conference on Connected Vehicles and Expo*, 2014, pp. 906–911.
- [47] M. Pavone, S. L. Smith, E. Frazzoli, and D. Rus, *Load Balancing for Mobility-on-Demand Systems*. Cambridge, MA: MIT Press, 2012.
- [48] M. Pavone, "Autonomous Mobility-on-Demand Systems for Future Urban Mobility," in *Autonomes Fahren*, M. Maurer, C. J. Gerdes, B. Lenz, and H. Winner, Eds. Springer Berlin Heidelberg, 2015, pp. 399–416.
- [49] B. Atasoy, T. Ikeda, X. Song, and M. E. Ben-Akiva, "The concept and impact analysis of a flexible mobility on demand system," *Transp. Res. Part C Emerg. Technol.*, vol. 56, pp. 373–392, 2015.
- [50] D. Papanikolaou and K. Larson, "Constructing Intelligence in Point-to-Point Mobility Systems," in *9th International Conference on Intelligent Environments*, 2013, pp. 51–56.
- [51] W. J. Mitchell, *Mobility on Demand: Future of transportation in cities*, no. November. Cambridge, MA: Massachusetts Institute of Technology, 2008.
- [52] M. Kreimeier, D. Gottschalk, and E. Stumpf, "Economical assessment of air mobility on demand concepts with focus on Germany," in *16th AIAA Aviation Technology, Integration, and Operations Conference*, 2016.
- [53] M. D. Moore, K. Goodrich, J. Viken, J. Smith, B. Fredericks, B. German, and M. Patterson, "High-Speed Mobility through On-Demand Aviation," in *13th AIAA Aviation Technology, Integration, and Operations Conference*, 2013, pp. 1–27.

- [54] M. Manville and D. Shoup, "Parking, People, and Cities," *J. Urban Plan. Dev.*, vol. 131, no. 4, pp. 233–245, 2005.
- [55] R. V. Hemm, D. Duncan, and V. L. Stouffer, "On-Demand Aviation Regulatory Obstacles and Resulting Research Roadmaps," *16th AIAA Aviat. Technol. Integr. Oper. Conf.*, no. June, pp. 1–14, 2016.
- [56] M. D. Moore, "Aviation Frontiers : On-Demand Aircraft," in *10th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference*, 2010, no. September, pp. 1–12.
- [57] T. R. Thompson and V. Stouffer, "Greenhouse Gas Impacts of On-Demand Electric Aircraft," in *15th AIAA Aviation Technology, Integration, and Operations Conference*, 2015, no. June 22-26, pp. 1–13.
- [58] D. Pu, A. A. Trani, and N. Hinze, "Zip Vehicle Commuter Aircraft Demand Estimate: a Multinomial Logit Mode Choice Model," in *14th AIAA Aviation Technology, Integration, and Operations Conference*, 2014, no. June 16-20, pp. 1–15.
- [59] B. A. Seeley, "Regional Sky Transit," in *15th AIAA Aviation Technology, Integration, and Operations Conference*, 2015.
- [60] B. A. Seeley, "Regional Sky Transit II," in *16th AIAA Aviation Technology, Integration, and Operations Conference*, 2016.
- [61] M. Moore and K. Goodrich, "On-Demand Mobility: Aviation's Path to High Speed Regional Mobility." Oshkosh, 2015.
- [62] AIRBUS, "Future of Urban Mobility: My kind of flyover," *FORUM*, 2016. [Online]. Available: <http://www.airbusgroup.com/int/en/news-media/corporate-magazine/Forum-88/My-Kind-Of-Flyover.html>. [Accessed: 12-Dec-2016].
- [63] R. Zhang, F. Rossi, and M. Pavone, "Model Predictive Control of Autonomous Mobility-on-Demand Systems," in *International Conference on Robotics and Automation*, 2016.
- [64] S. E. Underwood, "Disruptive Innovation on the Path to Sustainable Mobility," in *Road Vehicle Automation*, G. Meyer and S. Beiker, Eds. Switzerland: Springer International Publishing, 2014, pp. 157–168.
- [65] C. Muñoz, V. Carreño, and G. Dowek, "Formal Analysis of the Operational Concept for the Small Aircraft Transportation System," *Rigorous Dev. Complex Fault-Tolerant Syst.*, vol. 4157, pp. 306–325, 2006.
- [66] B. J. Holmes, M. H. Durham, and S. E. Tarry, "Small Aircraft Transportation System Concept and Technologies," *J. Aircr.*, vol. 41, no. 1, pp. 26–35, 2004.
- [67] A. Harish, C. Perron, D. Bavaro, J. Ahuja, M. Ozcan, C. Y. Justin, S. I. Briceno, B. J. German, and D. Mavis, "Economics of Advanced Thin-Haul Concepts and Operations," in *16th AIAA Aviation Technology, Integration, and Operations Conference*, 2016, no. June.
- [68] L. A. Kilgore, Godsey, Frank W., B. A. Rose, and F. B. Powers, "Electrical Airplane Propulsion," 2462201, 1949.
- [69] A. S. Gohardani, G. Doulgeris, and R. Singh, "Challenges of future aircraft propulsion: A review of distributed propulsion technology and its potential application for the all electric commercial aircraft," *Prog. Aerosp. Sci.*, vol. 47, no. 5, pp. 369–391, 2011.
- [70] P. D. Vascik, R. A. Pearce, and D. H. Rhodes, "Landscape Analysis Framework for Low Carbon Energy," in *15th AIAA Aviation Technology, Integration, and Operations Conference*, 2015, no. June.

- [71] J. D. Anderson, *Aircraft Performance and Design*. McGraw-Hill Companies, Inc., 1999.
- [72] M. Hepperle, “Electric Flight – Potential and Limitations,” in *AVT-209 Workshop on Energy Efficient Technologies and Concepts Operation*, 2012.
- [73] “Cirrus SR22,” 2013. [Online]. Available: <http://whycirrus.com/compare/compare.aspx>. [Accessed: 05-Apr-2016].
- [74] “Continental Motors 550 Gasoline Engine Series,” 2014. [Online]. Available: <http://www.continentalmotors.aero/uploadedFiles/Content/xImages/550Series-SpecSheet-WEB.pdf>.
- [75] M. D. Moore, “NASA Distributed Electric Propulsion Research,” in *Symposium E<sup>2</sup> Fliegen*, 2015.
- [76] J. Roskam, “Preliminary Sizing of Airplanes,” in *Airplane Design*, 4th ed., Lawrence, Kansas: DARcorporation, 2005.
- [77] P. M. Rothhaar, P. C. Murphy, B. J. Bacon, I. M. Gregory, J. A. Grauer, R. C. Busan, and M. A. Croom, “NASA Langley Distributed Propulsion VTOL Tilt - Wing Test Development,” in *14th AIAA Aviation Technology, Integration, and Operations Conference*, 2014, no. June, pp. 1–14.
- [78] U.S. Energy Information Administration, “Electric Power Annual 2015,” 2016. [Online]. Available: <http://www.eia.gov/electricity/annual/>. [Accessed: 01-Jan-2016].
- [79] AirNav, “Summary of fuel prices at 3686 FBOs nationwide,” *Fuel Price Report*, 2016. [Online]. Available: <https://www.airnav.com/fuel/report.html>. [Accessed: 01-Jan-2016].
- [80] S. Amarakoon, J. Smith, and B. Segal, “Application of Life-Cycle Assessment to Nanoscale Technology : Lithium-ion Batteries for Electric Vehicles,” Washington, DC, 2013.
- [81] D. A. Notter, M. Gauch, R. Widmer, W. A. Patrick, A. Stamp, R. Zah, and R. G. Althaus, “Contribution of Li-Ion Batteries to the Environmental Impact of Electric Vehicles,” *Environ. Sci. Technol.*, vol. 44, no. 17, pp. 6550–6556, 2010.
- [82] U.S. Environmental Protection Agency, “eGRID 2014 Summary Tables,” *Energy and the Environment*, 2017. [Online]. Available: <https://www.epa.gov/energy/egrid-2014-summary-tables>. [Accessed: 16-Jan-2017].
- [83] Cape Air, “Proposal of Hyannis Air Service, Inc., dba Cape Air to Provide Subsidized Essential Air Service To/From Lambert - St. Louis International Airport.” Cape Air, 2015.
- [84] P. Fairley, “Will Electric Vehicles Finally Succeed?,” *MIT Technology Review*, Cambridge, MA, p. 61, Jan-2011.
- [85] Y. Yao, W. Zhao, Ö. Ergun, and E. Johnson, “Crew Pairing and Aircraft Routing for On-Demand Aviation with Time Window,” Atlanta, GA, 2005.
- [86] S. Kim, T. Bandyopadhyay, B. Qin, Z. Jie, W. Liu, X. Shen, S. Pendleton, J. Guo, M. Fu, M. H. A. Jr, E. Frazzoli, and D. Rus, “Vehicle Autonomy Using Cooperative Perception for Mobility-on-Demand Systems,” in *Motion and Operation Planning of Robotic Systems*, vol. 29, G. Carbone and F. Gomez-Bravo, Eds. Springer International Publishing, 2015, pp. 331–360.
- [87] W. Knight, “Your Driverless Ride is Arriving,” *MIT Technology Review*, pp. 34–49, 2016.
- [88] D. J. Fagnant and K. Kockelman, “Preparing a nation for autonomous vehicles: Opportunities, barriers and policy recommendations,” *Transp. Res. Part A Policy Pract.*, vol. 77, pp. 167–181, 2015.

- [89] T. A. Litman, "Autonomous Vehicle Implementation Predictions," 2015. [Online]. Available: [www.vtpi.org](http://www.vtpi.org).
- [90] J. M. Anderson, N. Kalra, K. D. Stanley, P. Sorensen, C. Samaras, and O. A. Oluwatola, "Autonomous Vehicle Technology - A Guide for Policymakers," Washington, DC, 2014.
- [91] K. Spieser, K. Treleven, R. Zhang, E. Frazzoli, D. Morton, and M. Pavone, *Toward a Systematic Approach to the Design and Evaluation of Automated Mobility-on-Demand Systems : A Case Study in Singapore*. Springer International Publishing, 2014.
- [92] A. Downs, *Stuck in Traffic: Coping with Peak-Hour Traffic Congestion*. Washington, DC: The Brookings Institution, 1992.
- [93] H. Zureiqat, "Baumol's Cost Disease in Public Transit : Historical Evidence and Future Implications," in *Kuhmo Nectar Conference and Summer School*, 2007, pp. 9–13.
- [94] C. Anderson, *The Long Tail: Why the Future of Business is Selling Less of More*. New York, NY: Hyperion, 2006.
- [95] D. Locascio, M. Levy, K. Ravikumar, S. Briceno, B. German, and D. Mavris, "Evaluation of Concepts of Operations for On-Demand Package Delivery by Small Unmanned Aerial Systems," in *16th AIAA Aviation Technology, Integration, and Operations Conference*, 2016, no. June, pp. 1–15.
- [96] J. F. Coughlin, "The Tragedy of the Concrete Commons: Defining Traffic Congestion as a Public Problem," in *The Politics of Problem Definition: Shaping the Policy Agenda*, Lawrence, KS: University Press of Kansas, 1994, pp. 138–158.
- [97] NASA, *NASA Systems Engineering Handbook*, 1st ed. Washington, DC: NASA, 2007.
- [98] L. A. Macaulay, *Requirements Engineering (Applied Computing)*, 1st ed. Springer-Verlag London Limited, 1996.
- [99] R. Guillermin, H. Demmou, and N. Sadou, "Engineering Dependability Requirements for Complex Systems - A New Information Model Definition," in *2010 IEEE International Systems Conference Proceedings, SysCon 2010*, 2010, pp. 149–152.
- [100] M. Glinz, "On Non-Functional Requirements," in *15th IEEE International Requirements Engineering Conference*, 2007.
- [101] N. A. Ashford and C. C. Caldart, "Beyond Pollution Control and Prevention: Sustainable Development," in *Environmental Law, Policy and Economics*, Cambridge, MA: MIT Press, 2008, pp. 1043–1051.
- [102] R. Hickman, O. Ashiru, and D. Banister, "Achieving Carbon-Efficient Transportation," *Transp. Res. Rec. J. Transp. Res. Board*, vol. 2139, pp. 172–182, 2009.
- [103] D. Chattopadhyay, "A method for tradespace exploration of systems of systems," Massachusetts Institute of Technology, 2009.
- [104] P. D. Vascik, A. M. Ross, and D. H. Rhodes, "Program and Portfolio Tradeoffs Under Uncertainty Using Epoch-Era Analysis," in *26th Annual INCOSE International Symposium*, 2016.
- [105] J. Nickel, "Using Multi-Attribute Tradespace Exploration for the Architecting and Design of Transportation Systems," Massachusetts Institute of Technology, 2010.
- [106] C. Roberts, M. Richards, A. Ross, D. Rhodes, and P. D. Hastings, "Scenario Planning in Dynamic Multi-Attribute Tradespace Exploration," *3rd Annual IEEE Systems Conference*. IEEE, Vancouver, Canada, 2009.

- [107] J. Dahmann, G. Rebovich, R. Lowry, J. Lane, and K. Baldwin, “An Implementers’ View of Systems Engineering for Systems of Systems,” in *IEEE International Systems Conference*, 2011.
- [108] L. E. McCray, K. A. Oye, and A. C. Petersen, “Planned adaptation in risk regulation: An initial survey of US environmental, health, and safety regulation,” *Technol. Forecast. Soc. Change*, vol. 77, no. 6, pp. 951–959, 2010.
- [109] J. J. Laffont, *Externalities*, Second Edi. Palgrave Macmillan, 2008.
- [110] J. M. Viegas, “Making urban road pricing acceptable and effective: Searching for quality and equity in urban mobility,” *Transp. Policy*, vol. 8, no. 4, pp. 289–294, 2001.
- [111] J. Falk, Commonwealth Environment Protection Agency, and University of Wollongong: Technological Change and Environmental Strategies Group, *Social equity and the urban environment: report to the Commonwealth Environment Protection Agency*. Canberra: Australian Government Publication Service, 1993.
- [112] Federal Transit Administration, “Transportation , Environments Justice , and Social Equity Conference Proceedings,” 1995, no. July.
- [113] N. Pedersen, “Equity of evolving transportation finance mechanisms,” *Transportation Research Board of the National Academies*, no. 303. Washington, DC, 2011.
- [114] A. Karner and D. Niemeier, “Civil rights guidance and equity analysis methods for regional transportation plans: A critical review of literature and practice,” *J. Transp. Geogr.*, vol. 33, pp. 126–134, 2013.
- [115] K. Lowe, “Bypassing Equity? Transit Investment and Regional Transportation Planning,” *J. Plan. Educ. Res.*, vol. 34, no. 1, pp. 30–44, 2014.
- [116] C. Harlan, “A lonely road,” *The Washington Post*, 2015. [Online]. Available: <http://www.washingtonpost.com/sf/business/2015/12/28/deep-south-4/>. [Accessed: 01-Dec-2017].
- [117] S. L. Bottles, *Los Angeles and the Automobile*. Berkeley and Los Angeles, CA: University of California Press, 1987.
- [118] U.S. Environmental Protection Agency, “Environmental Justice,” 2017. [Online]. Available: <https://www.epa.gov/environmentaljustice>. [Accessed: 14-Jan-2017].
- [119] R. D. Bullard, “Environmental Justice as a Working Model,” in *Dumping in Dixie: Race, Class and Environmental Quality*, Boulder, CO: Westview Press, 1994.
- [120] R. Sims, R. Schaeffer, F. Creutzig, X. Cruz-Núñez, M. D’Agosto, D. Dimitriu, M. J. F. Meza, L. Fulton, S. Kobayashi, O. Lah, A. McKinnon, P. Newman, M. Ouyang, J. J. Schauer, D. Sperling, G. Tiwari, A. a. Amekudzi, B. S. M. C. Borba, H. Chum, P. Crist, H. Hao, J. Helfrich, T. Longden, A. F. P. De Lucena, P. Peeters, R. Plevin, S. Plotkin, R. Sausen, H. L. Raadal, L. Gagnon, I. S. Modahl, and O. J. Hanssen, “Transport,” in *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, O. Edenhofer, R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlomer, C. von Stechow, T. Zwickel, and J. C. Minx, Eds. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press, 2014, pp. 599–670.
- [121] D. Banister, K. Anderton, D. Bonilla, M. Givoni, and T. Schwanen, “Transportation and the Environment,” *Annu. Rev. Environ. Resour.*, vol. 36, no. 1, pp. 247–270, 2011.
- [122] M. L. Wald, “How Dreams of Clean Air Get Stuck in Traffic,” *New York Times*, New York, NY, p. E1, 11-

Mar-1990.

- [123] A. Schafer and D. Victor, "The Past and Future of Global Mobility," *Sci. Am.*, vol. 277, no. 4, pp. 58–61, 1997.
- [124] International Civil Aviation Organization, "What is CORSIA and how does it work?," *Environmental Protection*, 2017. [Online]. Available: [http://www.icao.int/environmental-protection/Pages/A39\\_CORZIA\\_FAQ2.aspx](http://www.icao.int/environmental-protection/Pages/A39_CORZIA_FAQ2.aspx). [Accessed: 15-Jan-2017].
- [125] N. Bartlett, R. Gerwatowski, D. Sieger, M. Suuberg, J. Judson, R. Hayden, J. Westbrook, A. O'Connor, L. Roy, G. Peterson, and J. Lebeaux, "Massachusetts Clean Energy and Climate Plan for 2020," Boston, MA, 2015.
- [126] A. Schwarzenegger, "Executive Order S-3-05." Office of the Governor, California, 2005.
- [127] G. D. Nelson and A. Rae, "An Economic Geography of the United States: From Commutes to Megaregions," *PLoS One*, vol. 11, no. 11, pp. 1–23, 2016.
- [128] America 2050, "Megaregions," *Regional Plan Association*, 2015. [Online]. Available: <http://www.america2050.org>. [Accessed: 01-Jan-2016].
- [129] Southern California Association of Governments, "The 2016-2040 Regional Transportation Plan/Sustainable Communities Strategy," Los Angeles, CA, 2016.
- [130] C. McShane, *Down the Asphalt Path: the Automobile and the American City*. New York, NY: Columbia University Press, 1994.
- [131] M. Pavone, K. Treleaven, and E. Frazzoli, "Fundamental performance limits and efficient policies for Transportation-On-Demand systems," in *49th IEEE Conference on Decision and Control (CDC)*, 2010, pp. 5622–5629.
- [132] M. Certický, M. Jakob, R. Píbil, and Z. Moler, "Agent-based Simulation Testbed for On-demand Transport Services," in *The 3rd International Workshop on Agent-based Mobility, Traffic and Transportation Models, Methodologies and Applications (ABMTRANS)*, 2014, vol. 32, pp. 808–815.
- [133] M. A. Rapino and A. K. Fields, "Mega Commuters in the US: Time and Distance in Defining the Long Commute using the American Community Survey," in *Association for Public Policy Analysis and Management Fall 2013 Conference*, 2013.
- [134] M. B. Teitz and E. Barbour, "Megaregions in California: Challenges to Planning and Policy," *The Healdsburg Research Seminar on Megaregions*. Healdsburg, CA, 2007.
- [135] K. Broder, "California Communities Dominate List of Mega-Commuters," 07-Mar-2013. [Online]. Available: <http://www.allgov.com/usa/ca/news/top-stories/california-communities-dominate-list-of-mega-commuters-130307?news=849347>.
- [136] S. R. Highley, "The Highley 1000 Neighborhoods," 2016. [Online]. Available: <http://highley1000.com/>. [Accessed: 20-May-2016].
- [137] K. Lynch, "The Pattern of the Metropolis," *Daedalus*, vol. 90, no. 1, pp. 79–98, 1961.
- [138] Transit Cooperative Research Program, *Transit Capacity and Quality of Service Manual*, 3rd ed. Washington, DC: Transportation Research Board, 2013.
- [139] M. Iacono, K. J. Krizek, and A. El-Geneidy, "Access to Destinations: How Close is Close Enough?"



- Estimating Accurate Distance Decay Functions for Multiple Modes and Different Purposes,” St. Paul, MINN., 2008.
- [140] A. W. Schäfer, “Long-term trends in domestic US passenger travel: the past 110 years and the next 90,” *Transportation (Amst)*, vol. in press, 2016.
- [141] J. Jiao and M. Dillivan, “Transit Deserts: The Gap between Demand and Supply,” *J. Public Transp.*, vol. 16, no. 3, pp. 23–39, 2013.
- [142] J. H. Kay, *Asphalt Nation: How the Automobile Took Over America and How We Can Take it Back*, 1st ed. Berkeley and Los Angeles, CA: University of California Press, 1997.
- [143] A. T. Durning, *The Car and the City*. Vancouver, B.C.: Northwest Environment Watch, 1996.
- [144] E. W. Soja, *My Los Angeles: From Urban Restructuring to Regional Urbanization*. Berkeley and Los Angeles, CA: University of California Press, 2014.
- [145] C. Curtis, “Planning for sustainable accessibility: The implementation challenge,” *Transp. Policy*, vol. 15, no. 2, pp. 104–112, 2008.
- [146] S. Angel and A. M. Blei, “COMMUTING AND THE SPATIAL STRUCTURE OF AMERICAN CITIES : The dispersal of the great majority of workplaces away from,” 20, 2015.
- [147] Bureau of Transportation Statistics, “Table 4-23: Average Fuel Efficiency of U.S. Light Duty Vehicles,” *National Transportation Statistics*, 2016. [Online]. Available: [https://www.rita.dot.gov/bts/sites/rita.dot.gov/bts/files/publications/national\\_transportation\\_statistics/html/table\\_04\\_23.html](https://www.rita.dot.gov/bts/sites/rita.dot.gov/bts/files/publications/national_transportation_statistics/html/table_04_23.html). [Accessed: 16-Jan-2017].
- [148] M. Barth and K. Boriboonsomsin, “Traffic Congestion and Greenhouse Gases,” *ACCESS*, Riverside, CA, Oct-2009.
- [149] P. Szoldra, “Ex-Google engineer reveals how Google Maps figures out destination times,” *Business Insider*, 2013. [Online]. Available: <http://www.businessinsider.com/google-maps-times-2013-12>. [Accessed: 23-Apr-2016].
- [150] R. a. Becker, R. Cáceres, K. Hanson, S. Isaacman, J. M. Loh, M. Martonosi, J. Rowland, S. Urbanek, a. Varshavsky, and C. Volinsky, “Human mobility characterization from cellular network data,” *Commun. ACM*, vol. 56, no. 1, p. 74, 2013.
- [151] M. C. González, C. A. Hidalgo, and A.-L. Barabási, “Understanding individual human mobility patterns,” *Nature*, vol. 453, no. 7196, pp. 779–782, 2008.
- [152] J. Garreau, *Edge City: Life on the New Frontier*. New York: Knopf Doubleday Publishing Group, 1991.
- [153] “MapCrunch: Random Street View,” 2016. [Online]. Available: [www.mapcrunch.com](http://www.mapcrunch.com). [Accessed: 12-Jun-2016].
- [154] Tesla Motors, “Model S Charging Estimator,” 2016. [Online]. Available: <https://www.teslamotors.com/models>. [Accessed: 07-Jul-2016].
- [155] C. Jones and D. M. Kammen, “Spatial Distribution of US Household Carbon Footprints Reveals Suburbanization Undermines Greenhouse Gas Benefits of Urban Population Density,” *Environ. Sci. Technol.*, 2013.
- [156] K. Storey, “Fly-in/fly-out: Implications for community sustainability,” *Sustainability*, vol. 2, no. 5, pp.

- 1161–1181, 2010.
- [157] C. McCoy, *3:16-cv-6-DJH: Memorandum in Support of Motion to Dismiss*. 2016.
- [158] T. C. Gleason and J. E. Mackler, *3:16-cv-6-DJH: Complaint for Declaratory Judgment and Damages*. 2016.
- [159] National Transportation Safety Board, “Documents Relating to Docket CP-217: Huerta v. Pirker,” 2016. [Online]. Available: <http://www.nts.gov/legal/alj/Pages/pirker.aspx>. [Accessed: 27-Oct-2016].
- [160] T. A. Heppenheimer, *Turbulent Skies: The history of commercial aviation*. John Wiley & Sons, Inc, 1995.
- [161] C. L. Scovel, “FAA’s Progress and Challenges in Advancing the Next Generation Air Transportation System,” Washington, DC, 2013.
- [162] Federal Aviation Administration, “Pilot’s Handbook of Aeronautical Knowledge,” *FAA-H-8083-25A*. U.S. Department of Transportation, Washington, DC, 2008.
- [163] G. J. Reigel, “Identification of a ‘Congested Area’ Under FAR § 91.119: Hindsight is 20/20,” *Reigel Law Firm, LTD. Aero Legal Services*, 2008. [Online]. Available: <http://www.aerolegalservices.com/Articles/Congested Areas Under FAR 91-119 2008-08-28.shtml>. [Accessed: 11-Jun-2016].
- [164] R. B. MacPherson, “Legal Interpretation of 14 C.F.R §91.119.” Federal Aviation Administration Office of the Chief Counsel, Washington, DC, pp. 1–3, 2010.
- [165] Federal Aviation Administration, “Aeronautical Information Manual,” Washington, DC, 2016.
- [166] Federal Aviation Administration, “AC 9-23G: Aircraft Wake Turbulence,” Washington, DC, 2014.
- [167] E. L. Ray, “Order JO 7110.65W.” U.S. Department of Transportation, Washington, DC, 2015.
- [168] Federal Aviation Administration, “New York City Special Flight Rules Area.” U.S. Department of Transportation, Washington, DC, 2009.
- [169] H. Beckman, “Taking of Property: Avigation Easements and Zoning Regulations,” *Aviation Noise Law*, 2015. [Online]. Available: <http://airportnoiselaw.org/takings.html>. [Accessed: 01-Aug-2016].
- [170] Federal Aviation Administration, “Busting Myths about the FAA and Unmanned Aircraft,” 2014. [Online]. Available: <https://www.faa.gov/news/updates/?newsId=76240>. [Accessed: 07-Oct-2016].
- [171] M. Connot and J. Zummo, “FAA Reauthorization Bill Attempts National Drone Policy,” 2016. [Online]. Available: <https://www.law360.com/articles/784512/faa-reauthorization-bill-attempts-national-drone-policy>.
- [172] J. A. Berger, “Phoenix Grounded: The Impact of the Supreme Court’s Changing Preemption Doctrine on State and Local Impediments to Airport Expansion,” *Northwest. Univ. Law Rev.*, vol. 97, no. 2, pp. 963–968, 2003.
- [173] R. A. Heverly, “The State of Drones: State Authority to Regulate Drones,” *Albany Gov. Law Rev.*, vol. 8, no. 29, pp. 29–62, 2015.
- [174] Federal Aviation Administration, “State and Local Regulation of Unmanned Aircraft Systems (UAS) Fact Sheet.” Washington, DC, 2015.
- [175] T. A. Rule, “Airspace in an Age of Drones,” *Bost. Univ. Law Rev.*, vol. 95, pp. 155–208, 2015.

- [176] A. M. Dolan and R. M. Thompson II, "Integration of Drones into Domestic Airspace: Selected Legal Issues," 2013.
- [177] Y. Abramovitch, "The Maxim 'Cujus Est Solum Ejus Usque Ad Coelum' as Applied in Aviation," *McGill Law J.*, vol. 8, no. 4, pp. 247–269, 1961.
- [178] S. Banner, *Who Ownes the Sky?* Cambridge, MA: Harvard University Press, 2008.
- [179] R. Luppiciini and A. So, "A Technoethical Review of Commercial Drone Use in the Context of Governance, Ethics, and Privacy," *Technol. Soc.*, vol. 46, pp. 109–119, 2016.
- [180] J. Villasenor, "Observations from above: Unmanned aircraft systems and privacy," *Harvard J. Law Public Policy*, vol. 36, no. 2, pp. 457–517, 2013.
- [181] A. Smith, "U.S. views of technology and the future: Science in the next 50 years," 2014. [Online]. Available: <http://www.pewinternet.org/2014/04/17/us-views-of-technology-and-the-future/>. [Accessed: 25-Oct-2016].
- [182] N. R. Turza, "How we should all learn to stop worrying and love commercial drones," *North Carolina J. Law Technol.*, vol. 319, no. 15, pp. 319–361, 2014.
- [183] Los Angeles World Airports, "Aircraft Noise Abatement Operating Procedures and Restrictions," in *LAX Rules and Regulations*, no. September, Los Angeles, CA, 2010.
- [184] D. Weikel, "Santa Monica council votes to close the city's airport by July 2018," *Los Angeles Times*, Los Angeles, CA, 24-Aug-2016.
- [185] Federal Aviation Administration, "AC No: 20-138D." Department of Transportation, Washington, DC, 2014.
- [186] M. Deehan, "U.S. Rep. Steve Lynch in dogfight with FAA over Logan airport route changes," *WGBH News*, 2015. [Online]. Available: <http://news.wgbh.org/post/us-rep-steve-lynch-dogfight-faa-over-logan-airport-route-changes>. [Accessed: 09-Oct-2016].
- [187] P. Burton, "Massport, FAA take steps to reduce aircraft noise in Boston area," *CBS Boston*, 2016. [Online]. Available: <http://boston.cbslocal.com/2016/10/07/massport-faa-logan-airport-milton-airplane-noise/>. [Accessed: 09-Oct-2016].
- [188] R. D. Steinbach, "Avigation Easements," 1998. [Online]. Available: <http://archives.ocgov.com/eltoroairportorg/issues/aveasement2.html>. [Accessed: 05-Nov-2016].
- [189] H. Beckman, "Can Avigation Easements Be Acquired by Prescription?," *Aviation Noise Law*, 2015. [Online]. Available: <http://airportnoiselaw.org/av-ease2.html>. [Accessed: 01-Aug-2016].
- [190] Forensic Appraisal Group Ltd., "Airport / Avigation." [Online]. Available: <http://www.forensic-appraisal.com/airport---avigation>. [Accessed: 11-Oct-2016].
- [191] Federal Aviation Administration, "Surface and Overhead Avigation Easement." U.S. Department of Transportation, Washington, DC, 2012.
- [192] G. Warwick, "Amazon, Google Want Changes to Low-Altitude Airspace for UAS," *Aviation Week & Space Technology*, 2015. [Online]. Available: <http://aviationweek.com/technology/amazon-google-want-changes-low-altitude-airspace-uas>. [Accessed: 01-Nov-2016].
- [193] City of Los Angeles, "Sec. 57.4705.4 Emergency Helicopter Landing Facility," *Los Angeles Municipal*

- Code*, 2013. [Online]. Available: [http://clkrep.lacity.org/onlinedocs/2013/13-0359\\_ord\\_182822.pdf](http://clkrep.lacity.org/onlinedocs/2013/13-0359_ord_182822.pdf).
- [194] Office of the Fire Marshal, “Los Angeles Fire Department Requirement No. 10,” 2014. [Online]. Available: [http://www.lafd.org/sites/default/files/pdf\\_files/EHLF-Reg10.pdf](http://www.lafd.org/sites/default/files/pdf_files/EHLF-Reg10.pdf). [Accessed: 01-May-2016].
- [195] Federal Aviation Administration, “AC 150/5390-2C: Helicopter Design,” Department of Transportation, Washington, DC, 2012.
- [196] W. J. Fredericks, “Impact of Operational Requirements on Intra-Urban VTOL Conceptual Design [ORAL PRESENTATION],” in *16th AIAA Aviation Technology, Integration, and Operations Conference*, 2016.
- [197] B. Carey, “For Now, FAA is not Considering Airspace Changes for Drones,” *AIN Online*, 2016. [Online]. Available: <http://www.ainonline.com/aviation-news/aerospace/2016-05-03/now-faa-not-considering-airspace-changes-drones>. [Accessed: 12-Nov-2016].
- [198] Federal Aviation Administration, “Significant Progress Report on the Los Angeles Helicopter Noise Initiative,” Washington, DC, 2015.
- [199] Federal Aviation Administration, “Airport Noise and Access Restrictions,” in *FAA Airport Compliance Manual. Order 5190.6B*, 1st ed., Washington, DC: Department of Transportation, 2009.
- [200] C. Cox and J. Leverton, “Fly Neighborly Guide,” 2016. [Online]. Available: <https://www.rotor.org/Operations/FlyNeighborly/FlyNeighborlyGuide.aspx>.
- [201] L. Leylekian, M. Lebrun, and P. Lempereur, “An Overview of Aircraft Noise Reduction Technologies,” *AerospaceLab*, vol. 1, no. 7, pp. 1–15, 2014.
- [202] S. Silva, “Human Factors Studies of an ADS-B Traffic Alerting System for General Aviation,” Massachusetts Institute of Technology, 2012.
- [203] United States Marine Corps, “Aviation Special Instructions,” 2007. [Online]. Available: [http://www.pendleton.marines.mil/Portals/98/Docs/Operations/RangeOps/Aviation\\_Ranges/airspace.pdf?ver=2012-09-27-133746-083](http://www.pendleton.marines.mil/Portals/98/Docs/Operations/RangeOps/Aviation_Ranges/airspace.pdf?ver=2012-09-27-133746-083).

## **Acronyms and Abbreviations**

**ACS** – U.S. Census Bureau’s American Community Survey  
**ADS-B** – Automatic Dependent Surveillance – Broadcast  
**AGL** – Above Ground Level  
**ASDE-X** – Airport Surface Detection Equipment Model X  
**ATC** – Air Traffic Control  
**ATM** – Air Traffic Management  
**AV** – Autonomous Vehicle  
**CALDOT** – California Department of Transportation  
**CBD** – Central Business District  
**CCR** – California Code of Regulations  
**ConOps** – Concept of Operations  
**CRS** – U.S. Congressional Research Service  
**dBA** – A-weighted Decibels  
**DEP** – Distributed Electric Propulsion  
**DFRA** – Dynamic Flight Rules Area  
**EEA** – Epoch-Era Analysis  
**EHLF** – Emergency Helicopter Landing Facility  
**EIA** – Environmental Impact Assessment  
**EMS** – Emergency Medical Services  
**EPA** – U.S. Environmental Protection Agency  
**eVFR** – Electronic Visual Flight Rules  
**FAA** – U.S. Federal Aviation Administration  
**FAR** – Federal Aviation Regulations  
**FATO** – Final Approach and Takeoff Area  
**GA** – General Aviation  
**GHG** – Greenhouse Gas  
**GPS** – Global Positioning System  
**IA** – Policy Impact Assessment  
**ICAO** – International Civil Aviation Organization  
**ICE** – Internal Combustion Engine  
**IFR** – Instrument Flight Rules  
**IMC** – Instrument Meteorological Conditions  
**IPCC** – Intergovernmental Panel on Climate Change  
**kWh** – Kilowatt Hour  
**L.A.** – Los Angeles  
**L/D** – Lift to Drag Ratio  
**LAX** – Los Angeles International Airport  
**LODES** – U.S. Census Bureau Longitudinal Employer-Household Dynamics Origin-Destination Employment Statistics  
**LOS** – Line of Sight  
**MaaS** – Mobility as a Service  
**MJ** – Mega Joule  
**MoD** – Mobility on Demand

**MPG** – Miles per Gallon  
**MPH** – Miles per Hour  
**MSL** – Mean Sea Level  
**MWh** – Megawhatt Hour  
**NAB** – Navigable Airspace Boundary  
**nmi** – Nautical Mile  
**ODM** – On Demand Mobility  
**PAV** – Personal Air Vehicle  
**PST** – Pacific Standard Time  
**PUC** – California Public Utilities Code  
**R&D** – Research and Development  
**RE** – Requirements Engineering  
**RNAV** – Area Navigation  
**RPM** – Revolutions Per Minute  
**RQ** – Research Question  
**SATS** – Small Aircraft Transportation System  
**SFRA** – Special Flight Rules Area  
**SIA** – Social Impact Assessment  
**SID** – Standard Instrument Departure  
**SM** – Statute Mile  
**SoS** – Systems of Systems  
**STAR** – Standard Terminal Arrival Route  
**TFR** – Temporary Flight Restriction  
**TLOF** – Touch-Down and Liftoff Area  
**TNC** – Transportation Network Company  
**TOLA** – Takeoff and Landing Area  
**TRL** – Technology Readiness Level  
**TSAA** – Traffic Situation Awareness with Alerting  
**UAS** – Unmanned Aircraft System  
**UTM** – Unmanned Aircraft System Traffic Management  
**V/STOL** – Vertical/Short Takeoff and Landing  
**VFR** – Visual Flight Rules  
**VLJ** – Very Light Jet  
**VMC** – Visual Meteorological Conditions  
**VTOL** – Vertical Takeoff and Landing

## Appendix A: Reference Mission Definitions

This appendix contains greater detail on the development of the reference missions that were not presented in full in Chapter 4.

### *San Bernardino to Glendale City Center Reference Mission*

Table 57 displays the specifications for the San Bernardino to Glendale City Center reference mission. The origin point was chosen in the only high value neighborhood in San Bernardino County, located in the foothills north of Rancho Cucamonga. The nearest currently available helipad is a private surface facility located in the hills 1.4 miles from the mission origin point. The mission destination point is an office building in the Glendale City Center with an onsite helipad.

Table 57. San Bernardino to Glendale City Center reference mission specifications.

|                             |   |                   |      |                     |
|-----------------------------|---|-------------------|------|---------------------|
| <b>Type:</b>                | Wealthy Commuter, Extreme Commuting                     |                   |      |                     |
| <b>Origin:</b>              | 11076 Hiddentrail Dr, Rancho Cucamonga, CA 91737        |                   |      |                     |
| <b>2016 Origin Helipad:</b> | Deer Canyon: 4552 Haven Ave, Rancho Cucamonga, CA 91737 |                   |      |                     |
| <b>Destination:</b>         | Downtown Glendale: 400 N Brand Blvd, Glendale, CA 91203 |                   |      |                     |
| <b>Destination Helipad:</b> | on-site   |                   |      |                     |
| <b>Driving Distance:</b>    | 44  | mi primary ground | 53.5 | mi secondary ground |
| <b>2016 ODM Distance:</b>   | 1.4   | mi to helipad     | 39   | mi LOS flight       |

Table 58 presents the ground transportation study for the San Bernardino to Glendale City Center reference mission. Ground transportation commuting times as predicted by the Google Maps™ mapping service were collected from 5:00 AM until 12:00 PM inbound from San Bernardino to Glendale, and from 1:00 PM until 8:00 PM outbound from Glendale to San Bernardino.

Table 58. San Bernardino to Glendale City Center reference mission ground transportation study.

|                 | Date      | Time  | Travel Time (minutes) |      |         |      | Avg. Speed (MPH) |
|-----------------|-----------|-------|-----------------------|------|---------|------|------------------|
|                 |           |       | Low                   | High | Average | +/-  |                  |
| <b>Inbound</b>  | 5/17/2016 | 5:00  | 50                    | 80   | 65      | 15   | 41               |
|                 | 5/17/2016 | 6:00  | 65                    | 140  | 102.5   | 37.5 | 26               |
|                 | 5/17/2016 | 7:00  | 75                    | 140  | 107.5   | 32.5 | 25               |
|                 | 5/17/2016 | 8:00  | 65                    | 110  | 87.5    | 22.5 | 30               |
|                 | 5/17/2016 | 9:00  | 55                    | 90   | 72.5    | 17.5 | 36               |
|                 | 5/17/2016 | 10:00 | 50                    | 80   | 65      | 15   | 41               |
|                 | 5/17/2016 | 11:00 | 50                    | 65   | 57.5    | 7.5  | 46               |
|                 | 5/17/2016 | 12:00 | 45                    | 65   | 55      | 10   | 48               |
| <b>Outbound</b> | 5/17/2016 | 13:00 | 45                    | 65   | 55      | 10   | 48               |
|                 | 5/17/2016 | 14:00 | 50                    | 75   | 62.5    | 12.5 | 42               |
|                 | 5/17/2016 | 15:00 | 65                    | 140  | 102.5   | 37.5 | 26               |
|                 | 5/17/2016 | 16:00 | 75                    | 160  | 117.5   | 42.5 | 22               |
|                 | 5/17/2016 | 17:00 | 75                    | 130  | 102.5   | 27.5 | 26               |
|                 | 5/17/2016 | 18:00 | 65                    | 100  | 82.5    | 17.5 | 32               |

|  |           |       |    |    |      |     |    |
|--|-----------|-------|----|----|------|-----|----|
|  | 5/17/2016 | 19:00 | 50 | 70 | 60   | 10  | 44 |
|  | 5/17/2016 | 20:00 | 45 | 60 | 52.5 | 7.5 | 50 |

Figure 96 presents the transportation study travel time and average speed distribution. The diagram is bimodal displaying the morning and evening “rush hour” periods arising from peak congestion. Interestingly, the rise in congestion begins earlier in the day for this reference mission than for the Malibu mission, having already become congested by 5:00 AM. This may indicate commuters are trying to avoid traffic by travelling earlier in the morning. Furthermore, the two peak periods are slower to drop off and rather asymmetric indicating that the roads remain congested for longer and that there are a significant number of individuals who travel into work after the peak period in the morning and return home after the peak period at night. Finally, the travel time estimation bounds are large during the morning and evening peak congestion periods, but become small in the afternoon. This indicates traffic flow is less than roadway capacity during the afternoon period.

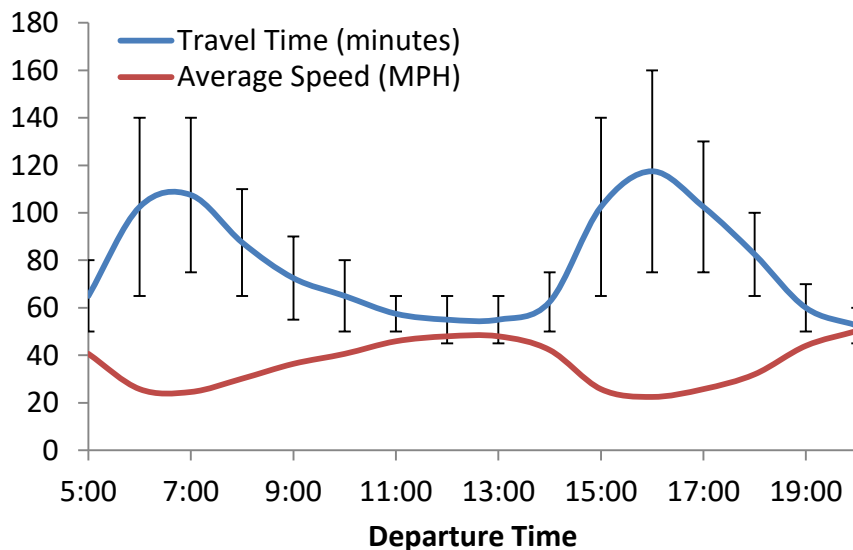


Figure 96. San Bernardino to Glendale City Center reference mission travel time and average speed distribution.

Finally, Figure 97 displays the inverse laborshed developed for the San Bernardino to Rancho Cucamonga reference mission. As can be seen, the largest number of workers commute south to downtown Rancho Cucamonga for work. The second greatest concentration of workers appears in downtown L.A. where 671 workers commute to each day; downtown L.A. is inscribed in black in Figure 97. Beyond those two common points, it appears that much of the L.A. basin has some number of workers from the reference area commuting there for work. Compared to Malibu, the workers in this reference area travel to a broader section of Los Angeles County to work. This may support the concept that San Bernardino and the Inland Empire are regions where a large percent of the population commutes from to Los Angeles County.

The Glendale City Center was found to have 85 individuals who commute to work from the reference region in Rancho Cucamonga. While this presents itself as a rather small early adopter market, ODM aviation services from this origin reference point to both the Glendale City Center and L.A. City Center would increase the number of potential passengers to over 750.



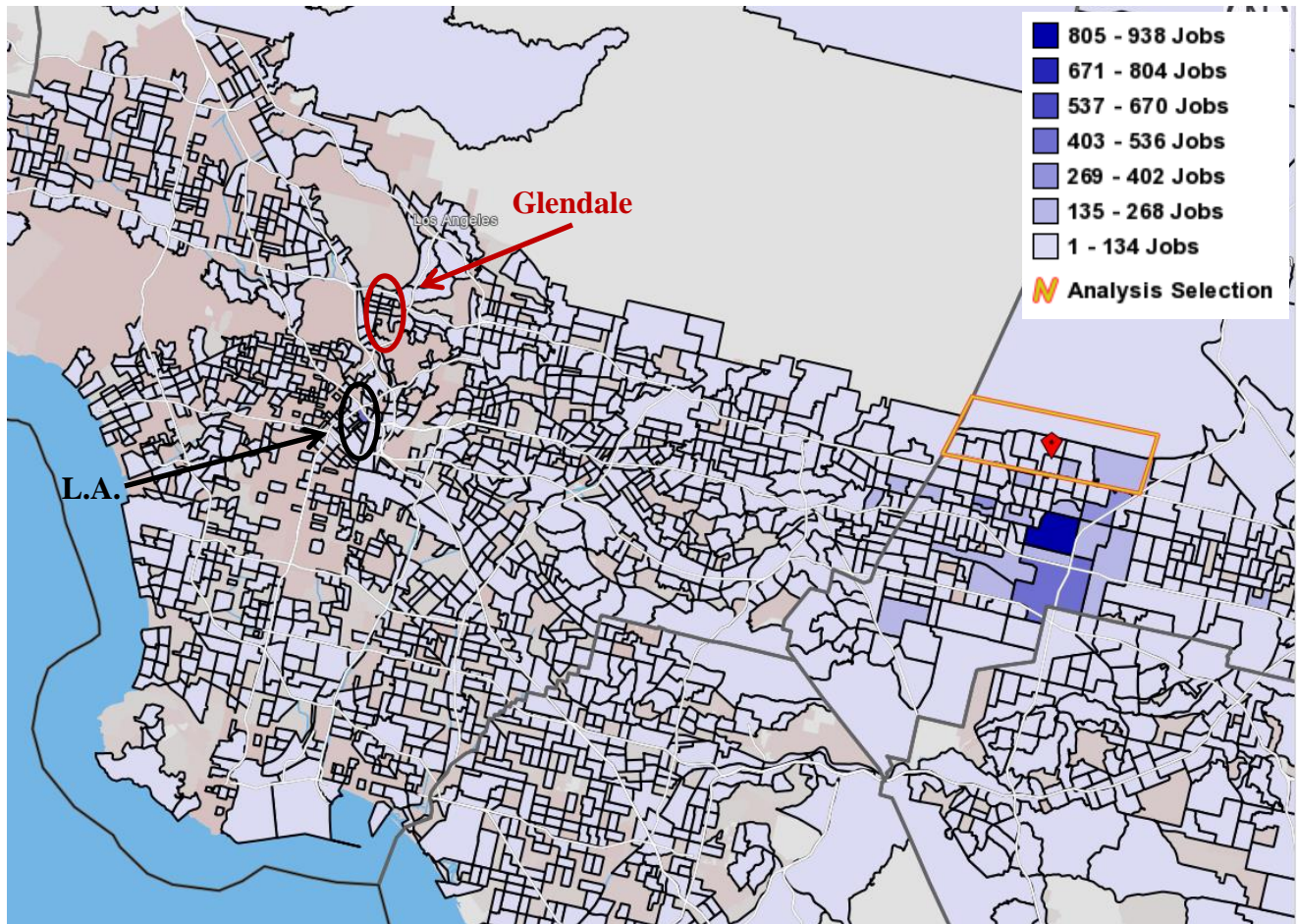


Figure 97. San Bernardino origin point inverse laborshed heat map with the Glendale City Center census tract indicated in red and Los Angeles City Center indicated in black. *Image developed with the U.S. Census Bureau OnTheMap application. <http://onthemap.ces.census.gov/>.*

### ***Antelope Valley to Los Angeles City Center Reference Mission***

Table 59 displays the specifications for the Antelope Valley to Los Angeles City Center reference mission. The mission origin point is a neighborhood west of downtown Lancaster. This neighborhood had an average valuation price around 300,000 dollars. The nearest currently available helipad is at the Palmdale airport located 11 miles from the origin point. The mission destination point is an office building in central Los Angeles with an onsite helipad.

Table 59. Antelope Valley to Los Angeles City Center reference mission specifications.

|                             |   |                   |      |                     |
|-----------------------------|---|-------------------|------|---------------------|
| <b>Type:</b>                | Mega Commuter   |                   |      |                     |
| <b>Origin:</b>              | 2336 W Avenue K, Lancaster, CA 93536                      |                   |      |                     |
| <b>2016 Origin Helipad:</b> | Palmdale Regional Airport: 20th Street East, Palmdale, CA |                   |      |                     |
| <b>Destination:</b>         | L.A. City Center: 633 W 5th St, Los Angeles, CA 90071     |                   |      |                     |
| <b>Destination Helipad:</b> | on-site   |                   |      |                     |
| <b>Driving Distance:</b>    | 61.5  | mi primary ground | 70.5 | mi secondary ground |
| <b>2016 ODM Distance:</b>   | 11  | mi to helipad     | 40.5 | mi LOS flight       |

Table 60 presents the ground transportation study for the Antelope Valley to Los Angeles City Center reference mission. Ground transportation commuting times were collected from 5:00 AM until 12:00 PM inbound from Antelope Valley to Los Angeles, and from 1:00 PM until 8:00 PM outbound from Los Angeles to the Antelope Valley.

Table 60. Antelope Valley to Los Angeles City Center reference mission ground transportation study.

|                 | Date      | Time  | Travel Time (minutes) |      |         |      | Avg. Speed (MPH) |
|-----------------|-----------|-------|-----------------------|------|---------|------|------------------|
|                 |           |       | Low                   | High | Average | +/-  |                  |
| <b>Inbound</b>  | 5/17/2016 | 5:00  | 80                    | 100  | 90      | 10   | 41               |
|                 | 5/17/2016 | 6:00  | 80                    | 110  | 95      | 15   | 39               |
|                 | 5/17/2016 | 7:00  | 90                    | 130  | 110     | 20   | 34               |
|                 | 5/17/2016 | 8:00  | 85                    | 110  | 97.5    | 12.5 | 38               |
|                 | 5/17/2016 | 9:00  | 80                    | 100  | 90      | 10   | 41               |
|                 | 5/17/2016 | 10:00 | 80                    | 100  | 90      | 10   | 41               |
|                 | 5/17/2016 | 11:00 | 75                    | 90   | 82.5    | 7.5  | 45               |
|                 | 5/17/2016 | 12:00 | 75                    | 90   | 82.5    | 7.5  | 45               |
| <b>Outbound</b> | 5/17/2016 | 13:00 | 80                    | 100  | 90      | 10   | 41               |
|                 | 5/17/2016 | 14:00 | 75                    | 100  | 87.5    | 12.5 | 42               |
|                 | 5/17/2016 | 15:00 | 80                    | 100  | 90      | 10   | 41               |
|                 | 5/17/2016 | 16:00 | 85                    | 110  | 97.5    | 12.5 | 38               |
|                 | 5/17/2016 | 17:00 | 85                    | 120  | 102.5   | 17.5 | 36               |
|                 | 5/17/2016 | 18:00 | 85                    | 110  | 97.5    | 12.5 | 38               |
|                 | 5/17/2016 | 19:00 | 80                    | 100  | 90      | 10   | 41               |
|                 | 5/17/2016 | 20:00 | 80                    | 90   | 85      | 5    | 43               |

Figure 98 presents the transportation study travel time and average speed distribution. The diagram displays a moderate bimodal trend revealing minor morning and evening peak congestion periods. The variance in travel times for this reference mission was less than for either of the previous commuter missions. This may indicate that the long duration of this reference mission is primarily due to the significant distance of the mission, rather than congestion on the roads. This interpretation is further supported by the finding that the most severe congestion period for this mission caused a little over a 60% time penalty, as compared to the 255% time penalty for the San Bernardino mission. Finally, the travel time estimation bounds are quite large for a majority of the day indicating that congestion is fairly stable for this route.

These patterns, shown in Figure 98, may suggest ODM aircraft services will be desired regularly throughout the day to cover the mega commute distance, rather than just during congested “rush hours” as may be the case for other reference missions.

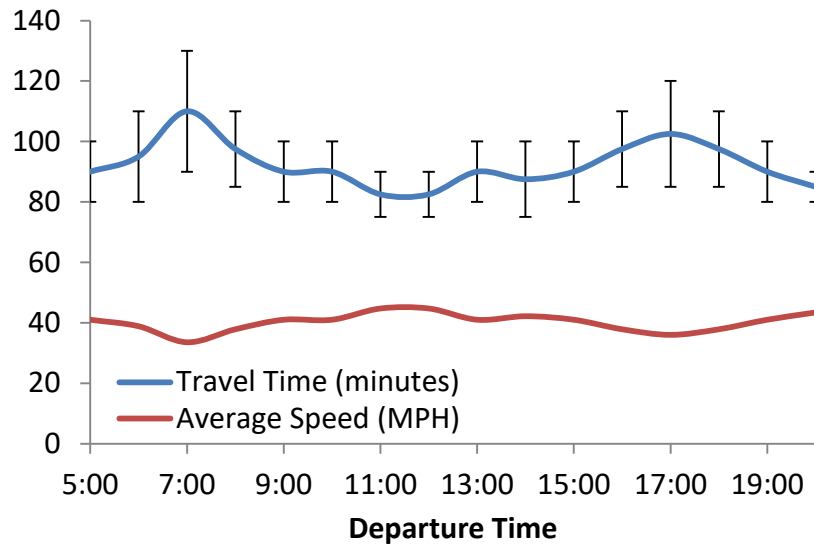


Figure 98. Antelope Valley to Los Angeles City Center reference mission travel time and average speed distribution.

Finally, Figure 99 displays the inverse laborshed developed for the Antelope Valley origin community. As may be seen in Figure 99, the largest number of workers remain in the Antelope Valley for work. The next concentration of workers appears in the Santa Clarita area where highway 14 intersects with Interstate 5 before entering the San Fernando Valley. There is also a dark blue census tract in the center of downtown L.A. indicating a significant number of people from the Antelope Valley commute the full distance to L.A. each day. Upon investigation, it was determined that 951 individuals commute from the reference region in Lancaster to downtown Los Angeles.

Of the three daily commuter reference missions conducted, this mission presents the largest potential market. Furthermore, this market is not necessarily limited to the peak congestion periods like the Malibu or San Bernardino missions because the trip requires over 75 minutes of travel each way by automobile independent of whether or not it is rush hour. Finally, the destination location for the residents from the reference region in Lancaster is highly concentrated in downtown Los Angeles. This may provide operational benefits for ODM aircraft services by enabling the pooling of passengers, as well as the use of a centralized pickup and drop-off location. While this reference mission does not involve one of the potential high income commuter communities, it is still promising as an early adopter market for ODM aircraft operations.

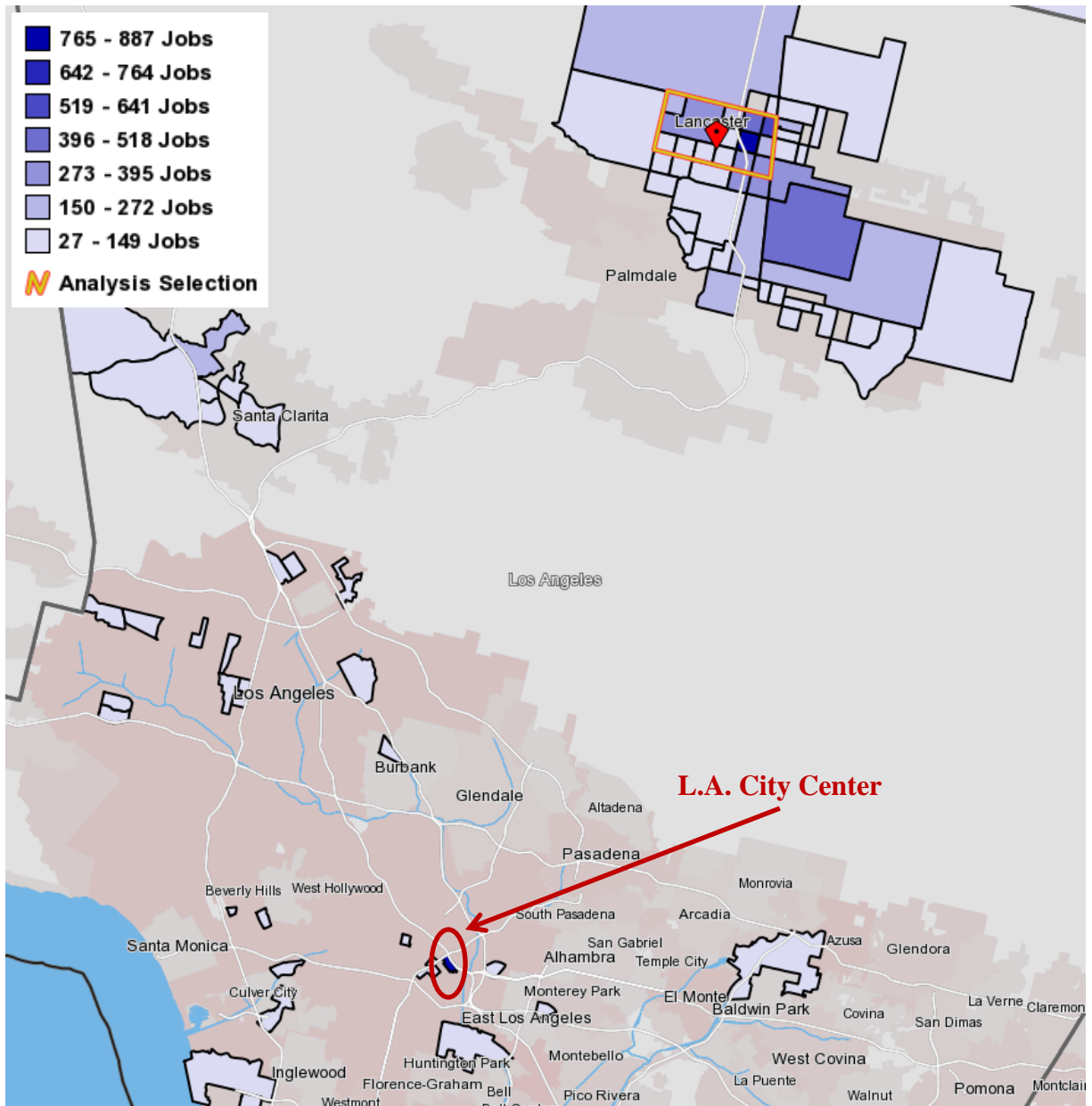


Figure 99. Antelope Valley origin point inverse laborshed heat map with the Los Angeles City Center census tract indicated in red. *Image developed with the U.S. Census Bureau OnTheMap application. <http://onthemap.ces.census.gov/>.*

***San Diego City Center to Los Angeles City Center Reference Mission***

Table 61 displays the specifications for the San Diego to Los Angeles City Center reference mission. The U.S. Bank branch in One America Plaza, San Diego, was selected as the mission origin point. The mission destination point was set as the U.S. Bank Tower in central Los Angeles. The nearest currently available helipad to One America Plaza is an EHLF at the Westin Hotel located one block away. The U.S. Bank Tower in Los Angeles has an onsite EHLF that is taken as the destination helipad.

Table 61. San Diego to Los Angeles City Center reference mission specifications.

|                             |  |                   |       |                     |
|-----------------------------|--|-------------------|-------|---------------------|
| <b>Type:</b>                | Inter-Urban  |                   |       |                     |
| <b>Origin:</b>              | One America Plaza, 600 W Broadway, San Diego, CA 92101 |                   |       |                     |
| <b>2016 Origin Helipad:</b> | Westin Helipad: 400 W Broadway, San Diego, CA 92101    |                   |       |                     |
| <b>Destination:</b>         | L.A. City Center: 633 W 5th St, Los Angeles, CA 90071  |                   |       |                     |
| <b>Destination Helipad:</b> | on-site  |                   |       |                     |
| <b>Driving Distance:</b>    | 122  | mi primary ground | 128   | mi secondary ground |
| <b>2016 ODM Distance:</b>   | 0.1  | mi to helipad     | 111.5 | mi LOS flight       |

Table 62 presents the ground transportation study for the San Diego to Los Angeles City Center reference mission. Ground transportation commuting times were predicted by the Google Maps™ mapping service. Unlike the commuter ODM aircraft reference missions, the non-commute point-to-point reference missions were considered only one-way, and the direction of travel was not flipped at one in the afternoon.

Table 62. San Diego to Los Angeles City Center reference mission ground transportation study.

|                | Date      | Time  | Travel Time (minutes) |      |         |     | Avg. Speed (MPH) |
|----------------|-----------|-------|-----------------------|------|---------|-----|------------------|
|                |           |       | Low                   | High | Average | +/- |                  |
| <b>Inbound</b> | 5/17/2016 | 5:00  | 130                   | 210  | 170     | 40  | 43               |
|                | 5/17/2016 | 6:00  | 140                   | 220  | 180     | 40  | 41               |
|                | 5/17/2016 | 7:00  | 150                   | 210  | 180     | 30  | 41               |
|                | 5/17/2016 | 8:00  | 140                   | 200  | 170     | 30  | 43               |
|                | 5/17/2016 | 9:00  | 130                   | 180  | 155     | 25  | 47               |
|                | 5/17/2016 | 10:00 | 120                   | 160  | 140     | 20  | 52               |
|                | 5/17/2016 | 11:00 | 120                   | 170  | 145     | 25  | 50               |
|                | 5/17/2016 | 12:00 | 120                   | 170  | 145     | 25  | 50               |
|                | 5/17/2016 | 13:00 | 120                   | 180  | 150     | 30  | 49               |
|                | 5/17/2016 | 14:00 | 130                   | 210  | 170     | 40  | 43               |
|                | 5/17/2016 | 15:00 | 150                   | 240  | 195     | 45  | 38               |
|                | 5/17/2016 | 16:00 | 160                   | 220  | 190     | 30  | 39               |
|                | 5/17/2016 | 17:00 | 140                   | 190  | 165     | 25  | 44               |
|                | 5/17/2016 | 18:00 | 120                   | 160  | 140     | 20  | 52               |
|                | 5/17/2016 | 19:00 | 110                   | 150  | 130     | 20  | 56               |
| 5/17/2016      | 20:00     | 110   | 140                   | 125  | 15      | 59  |                  |

Figure 100 presents the transportation study travel time and average speed distribution. The diagram displays a moderate bimodal trend revealing congestion periods from roughly 5:00 AM to 8:00 AM, and 2:00 PM to 5:00 PM. There is an average potential delay (uncertainty) of around 20%. The long distance of transportation from San Diego to Los Angeles suggests ODM aircraft services may be desired regularly, and not necessarily just during the congested “rush hours.”

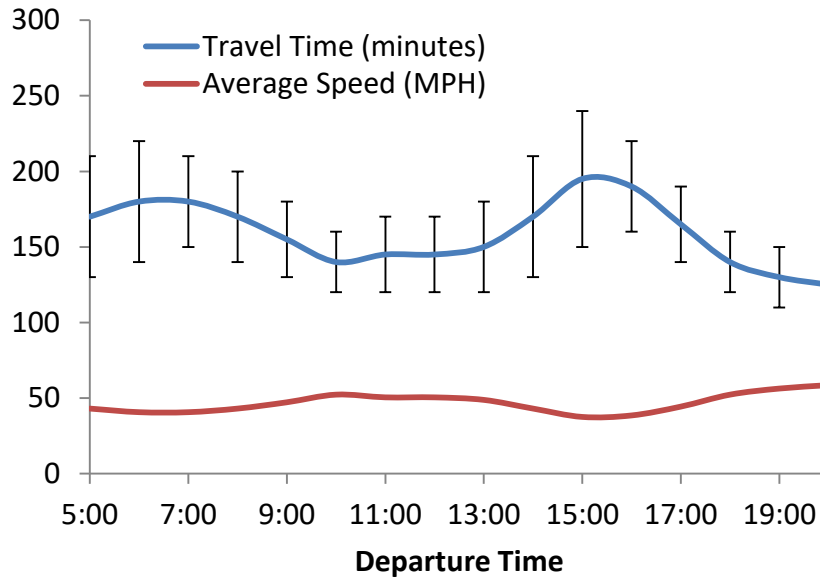


Figure 100. San Diego to Los Angeles City Center reference mission travel time and average speed distribution.

### ***Los Angeles City Center to Long Beach Reference Mission***

Table 63 displays the specifications for the Los Angeles City Center to Long Beach reference mission. Olvera Street, a historic marketplace and popular tourism destination in downtown Los Angeles, was selected as the mission origin point. The mission destination point was selected as the public access point to the Long Beach city beach. The nearest currently available helipad to Olvera is an EHLF located on a rooftop two blocks west of the marketplace. The nearest existing helipad is also an EHLF located on the roof of a beachside hotel roughly 0.7 miles west of the beach access point. Table 64 presents the ground transportation study for the Los Angeles City Center to Long Beach reference mission.

Table 63. Los Angeles City Center to Long Beach reference mission specifications.

|                             |  |                   |      |                     |
|-----------------------------|--|-------------------|------|---------------------|
| <b>Type:</b>                | Inter-City Center  |                   |      |                     |
| <b>Origin:</b>              | Olvera Street: 845 N Alameda St, Los Angeles, CA 90012     |                   |      |                     |
| <b>2016 Origin Helipad:</b> | EHLF: 600 N Broadway, Los Angeles, CA 90012                |                   |      |                     |
| <b>Destination:</b>         | 1 Junipero Ave, Long Beach, CA 90803                       |                   |      |                     |
| <b>Destination Helipad:</b> | 1310 E Ocean Blvd, Long Beach, CA 90802 (0.7 miles, 5 min) |                   |      |                     |
| <b>Driving Distance:</b>    | 26.5   | mi primary ground | 28.2 | mi secondary ground |
| <b>2016 ODM Distance:</b>   | 0.2  | mi to helipad     | 20.5 | mi LOS flight       |

Table 64. Los Angeles City Center to Long Beach reference mission ground transportation study.

|                |           | Travel Time (minutes) |      |         |      | Avg. Speed (MPH) |    |
|----------------|-----------|-----------------------|------|---------|------|------------------|----|
| Date           | Time      | Low                   | High | Average | +/-  |                  |    |
| <b>Inbound</b> | 5/17/2016 | 5:00                  | 30   | 40      | 35   | 5                | 45 |
|                | 5/17/2016 | 6:00                  | 30   | 45      | 37.5 | 7.5              | 42 |
|                | 5/17/2016 | 7:00                  | 35   | 65      | 50   | 15               | 32 |
|                | 5/17/2016 | 8:00                  | 35   | 55      | 45   | 10               | 35 |
|                | 5/17/2016 | 9:00                  | 35   | 50      | 42.5 | 7.5              | 37 |
|                | 5/17/2016 | 10:00                 | 35   | 50      | 42.5 | 7.5              | 37 |
|                | 5/17/2016 | 11:00                 | 35   | 50      | 42.5 | 7.5              | 37 |
|                | 5/17/2016 | 12:00                 | 35   | 50      | 42.5 | 7.5              | 37 |
|                | 5/17/2016 | 13:00                 | 35   | 50      | 42.5 | 7.5              | 37 |
|                | 5/17/2016 | 14:00                 | 35   | 60      | 47.5 | 12.5             | 33 |
|                | 5/17/2016 | 15:00                 | 45   | 75      | 60   | 15               | 27 |
|                | 5/17/2016 | 16:00                 | 50   | 90      | 70   | 20               | 23 |
|                | 5/17/2016 | 17:00                 | 55   | 100     | 77.5 | 22.5             | 21 |
|                | 5/17/2016 | 18:00                 | 50   | 85      | 67.5 | 17.5             | 24 |
|                | 5/17/2016 | 19:00                 | 40   | 65      | 52.5 | 12.5             | 30 |
| 5/17/2016      | 20:00     | 35                    | 45   | 40      | 5    | 40               |    |

Figure 101 presents the transportation study travel time and average speed distribution. The diagram displays a relatively stable predicted travel time in the morning until 2:00 PM, but then a significant congestion period in the evening from 2:00 PM until 7:00 PM. At 5:00 PM a peak congestion penalty of 230% is shown.

The shape of the Los Angeles City Center to Long Beach reference mission travel time distribution is different than any of the other reference missions that have been shown. The single modal shape indicates that a morning congestion period does not exist, perhaps in part because the mission would be a reverse commute out of the Los Angeles CBD. Secondly, the severity of the evening rush hour suggests the popularity of commuting southward from Los Angeles, as well as potentially the popularity of traveling to Long Beach in the evening. The characteristics of this reference mission suggest demand may exist for ODM aircraft services during the evening rush hour period, though not necessarily at any other time.

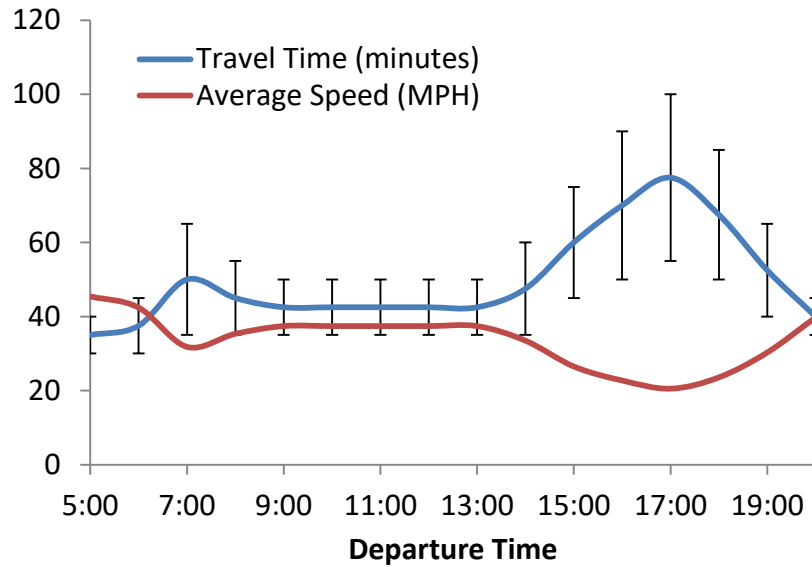


Figure 101. Los Angeles City Center to Long Beach reference mission travel time and average speed distribution.

### ***The Beverly Hills Hotel to Los Angeles Airport Reference Mission***

Table 65 displays the specifications for the Beverly Hills Hotel to Los Angeles Airport reference mission. The Beverly Hills Hotel is a historic landmark and five star luxury hotel on Sunset Boulevard. The hotel often hosts wealthy guests who use helicopter charter services in other settings, and therefore represents a likely early adopter market for ODM aircraft services should such services be available. The mission destination is the Los Angeles International Airport which is the primary airport in Southern California and common arrival and departure point for tourists and travelers.

The nearest currently available helipad to the Beverly Hills Hotel is an EHLF located on a high-rise apartment complex two miles southwest of the hotel on Wilshire boulevard. LAX has a multi-pad heliport located adjacent to the main terminal, however the facility has been closed since October 2010 and is not expected to re-open. Despite the current state of the heliport, it was considered as the destination point for this reference mission.

Table 65. Beverly Hills Hotel to Los Angeles Airport reference mission specifications.

|                             |   |                   |      |                     |
|-----------------------------|---|-------------------|------|---------------------|
| <b>Type:</b>                | Intra-City  |                   |      |                     |
| <b>Origin:</b>              | The Beverly Hills Hotel, 9641 Sunset Boulevard, Beverly Hills, CA 90210 |                   |      |                     |
| <b>2016 Origin Helipad:</b> | Beverly West Residences: 1200 Club View Dr, Los Angeles, CA 90024       |                   |      |                     |
| <b>Destination:</b>         | LAX: 380 World Way, Los Angeles, CA 90045                               |                   |      |                     |
| <b>Destination Helipad:</b> | on-site   |                   |      |                     |
| <b>Driving Distance:</b>    | 13  | mi primary ground | 15.7 | mi secondary ground |
| <b>2016 ODM Distance:</b>   | 2   | mi to helipad     | 8.6  | mi LOS flight       |



Table 66 presents the ground transportation study for the Beverly Hills Hotel to Los Angeles Airport reference mission.

Table 66. Beverly Hills Hotel to Los Angeles Airport reference mission ground transportation study.

|                | Date      | Time  | Travel Time (minutes) |      |         |      | Avg. Speed (MPH) |
|----------------|-----------|-------|-----------------------|------|---------|------|------------------|
|                |           |       | Low                   | High | Average | +/-  |                  |
| <b>Inbound</b> | 5/17/2016 | 5:00  | 26                    | 35   | 30.5    | 4.5  | 26               |
|                | 5/17/2016 | 6:00  | 26                    | 40   | 33      | 7    | 24               |
|                | 5/17/2016 | 7:00  | 28                    | 50   | 39      | 11   | 20               |
|                | 5/17/2016 | 8:00  | 30                    | 60   | 45      | 15   | 17               |
|                | 5/17/2016 | 9:00  | 30                    | 60   | 45      | 15   | 17               |
|                | 5/17/2016 | 10:00 | 28                    | 55   | 41.5    | 13.5 | 19               |
|                | 5/17/2016 | 11:00 | 28                    | 55   | 41.5    | 13.5 | 19               |
|                | 5/17/2016 | 12:00 | 30                    | 60   | 45      | 15   | 17               |
|                | 5/17/2016 | 13:00 | 30                    | 60   | 45      | 15   | 17               |
|                | 5/17/2016 | 14:00 | 35                    | 70   | 52.5    | 17.5 | 15               |
|                | 5/17/2016 | 15:00 | 40                    | 85   | 62.5    | 22.5 | 12               |
|                | 5/17/2016 | 16:00 | 45                    | 90   | 67.5    | 22.5 | 12               |
|                | 5/17/2016 | 17:00 | 45                    | 90   | 67.5    | 22.5 | 12               |
|                | 5/17/2016 | 18:00 | 40                    | 80   | 60      | 20   | 13               |
|                | 5/17/2016 | 19:00 | 35                    | 70   | 52.5    | 17.5 | 15               |
| 5/17/2016      | 20:00     | 30    | 55                    | 42.5 | 12.5    | 18   |                  |

Figure 102 presents the transportation study travel time and average speed distribution for this reference mission. Once again, similar to the Long Beach mission, this reference mission presents a single peak congestion mode during the evening rush hour. However, among all the reference missions presented in this study, this mission had the slowest average speed at just 17 miles per hour, with a high of 26 mph at 5:00 AM, and a low of 12 mph from 3:00 PM to 5:00 PM. Furthermore, the variance of the travel time is consistently large throughout the day indicating that the severity of congestion on the route is difficult to anticipate and varies dramatically. The lack of consistency, even more than the long average travel time, is especially challenging for travel to an airport and often requires a traveler to assume the worst case congestion scenario when planning their transportation.

These characteristics suggest that significant demand may exist for ODM aircraft services from the Beverly Hills Hotel to the Los Angeles International Airport. The high average wealth of the consumers, short distance, slow average ground speed, and volatile congestion on highway 405 may formulate high demand and an early adopting base of customers for ODM aircraft services. A limiting factor for this reference mission, however, is the lack of ground infrastructure near the Beverly Hills Hotel, and the current closure of the LAX heliport. These factors were investigated further through the development of mission ConOps.

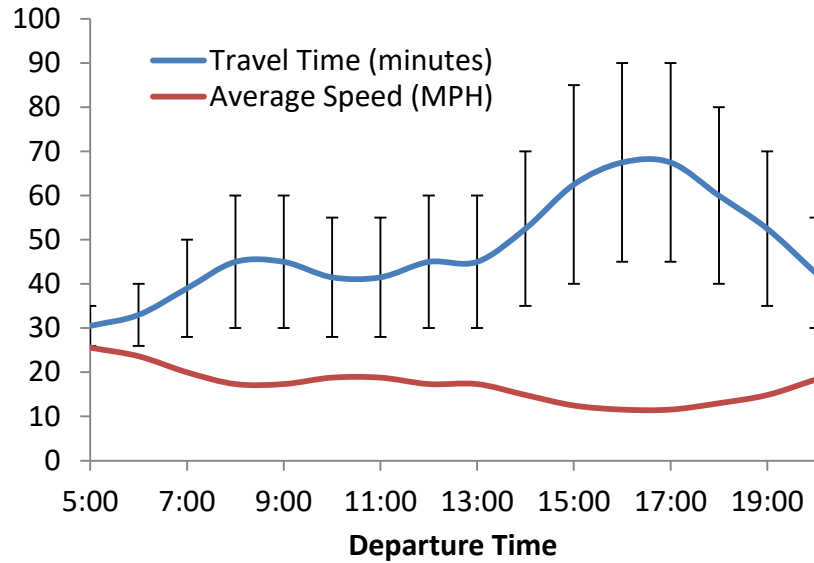


Figure 102. Beverly Hills Hotel to Los Angeles Airport reference mission travel time and average speed distribution.

### ***Redondo Beach to Dodger Stadium Reference Mission***

Table 67 displays the specifications for the Redondo Beach to Dodger Stadium reference mission. The mission origin point was chosen as a private home in the suburbs of Redondo Beach. The average home valuation in the chosen neighborhood is over one million dollars indicating residents in this area may be a potential early adopting market for ODM aircraft services. The mission destination is Dodger Stadium which is located just north of the L.A. City Center.

The nearest currently available helipad to the Redondo Beach origin point located in this research is at the Torrance Airfield 4.3 miles to the southeast. The proposed currently available destination helipad is a private use helipad located on a commercial building 1.3 miles south of the stadium. The lack of nearby ground infrastructure may limit the potential early adopter market for this reference mission as clients may still experience severe ground congestion as they travel from the current helipad to enter into the stadium. Table 68 presents the ground transportation study for the Redondo Beach to Dodger Stadium reference mission.

Table 67. Redondo Beach to Dodger Stadium reference mission specifications.

|                             |  |                   |      |                     |
|-----------------------------|--|-------------------|------|---------------------|
| <b>Type:</b>                | Intra-City   |                   |      |                     |
| <b>Origin:</b>              | 129 S Juanita Ave Redondo Beach, CA 90277                    |                   |      |                     |
| <b>2016 Origin Helipad:</b> | Torrance Airport: 3301 Airport Dr, Torrance, CA 90505        |                   |      |                     |
| <b>Destination:</b>         | Dodger Stadium, 1000 Elysian Park Ave, Los Angeles, CA 90012 |                   |      |                     |
| <b>Destination Helipad:</b> | 1000 W Temple St Los Angeles, CA 90012 (1.3 mi)              |                   |      |                     |
| <b>Driving Distance:</b>    | 22.7   | mi primary ground | 24.9 | mi secondary ground |
| <b>2016 ODM Distance:</b>   | 4.3  | mi to helipad     | 18.7 | mi LOS flight       |

Table 68. Redondo Beach to Dodger Stadium reference mission ground transportation study.

|                | Date      | Time  | Travel Time (minutes) |      |         |      | Avg. Speed (MPH) |
|----------------|-----------|-------|-----------------------|------|---------|------|------------------|
|                |           |       | Low                   | High | Average | +/-  |                  |
| <b>Inbound</b> | 5/17/2016 | 5:00  | 35                    | 40   | 37.5    | 2.5  | 36               |
|                | 5/17/2016 | 6:00  | 40                    | 75   | 57.5    | 17.5 | 24               |
|                | 5/17/2016 | 7:00  | 55                    | 100  | 77.5    | 22.5 | 18               |
|                | 5/17/2016 | 8:00  | 55                    | 100  | 77.5    | 22.5 | 18               |
|                | 5/17/2016 | 9:00  | 45                    | 80   | 62.5    | 17.5 | 22               |
|                | 5/17/2016 | 10:00 | 40                    | 70   | 55      | 15   | 25               |
|                | 5/17/2016 | 11:00 | 40                    | 70   | 55      | 15   | 25               |
|                | 5/17/2016 | 12:00 | 40                    | 65   | 52.5    | 12.5 | 26               |
|                | 5/17/2016 | 13:00 | 40                    | 70   | 55      | 15   | 25               |
|                | 5/17/2016 | 14:00 | 45                    | 75   | 60      | 15   | 23               |
|                | 5/17/2016 | 15:00 | 50                    | 100  | 75      | 25   | 18               |
|                | 5/17/2016 | 16:00 | 60                    | 130  | 95      | 35   | 14               |
|                | 5/17/2016 | 17:00 | 65                    | 120  | 92.5    | 27.5 | 15               |
|                | 5/17/2016 | 18:00 | 60                    | 100  | 80      | 20   | 17               |
|                | 5/17/2016 | 19:00 | 40                    | 65   | 52.5    | 12.5 | 26               |
|                | 5/17/2016 | 20:00 | 35                    | 50   | 42.5    | 7.5  | 32               |

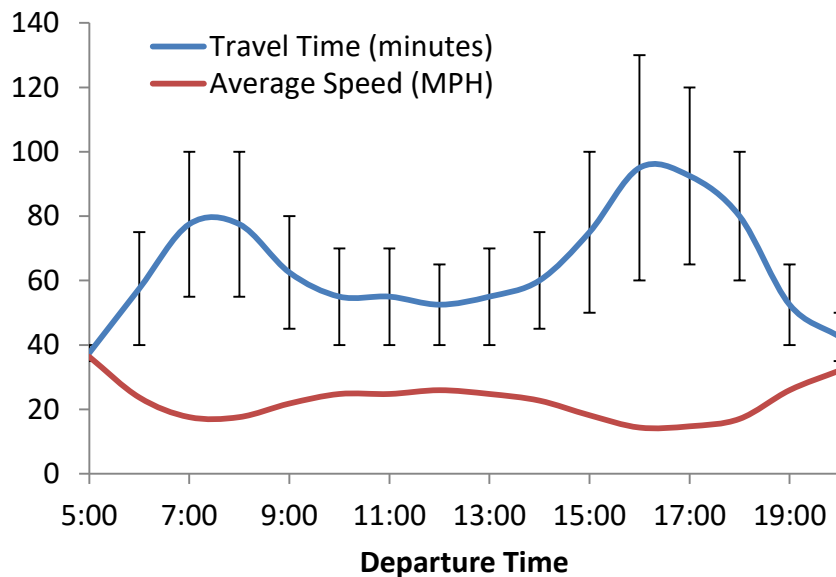


Figure 103. Redondo Beach to Dodger Stadium reference mission travel time and average speed distribution.

Figure 103 presents the transportation study travel time and average speed distribution. The distribution is bimodal displaying morning and evening peak congestion times. The evening rush hour is more severe, however, and corresponds to the travel time most individuals would experience when attending an evening weekday Dodgers game. Furthermore, the bounds on the

travel time are especially large during these peak congestion times indicating travel times may vary greatly. Once an additional congestion penalty is added to the trip to represent the game day traffic, the trip time could consistently surpass two hours.

These characteristics suggest that significant demand may exist for ODM aircraft services from Redondo Beach to Dodger Stadium. The extensive duration of travel and lack of consistency in travel time, especially considering the average 7:10 PM start time of Dodgers games, may encourage potential consumers to use ODM aircraft services to avoid leaving work early or chance missing the start of the game. A limiting factor for this reference mission is the lack of ground infrastructure near the suburban origin point in Redondo Beach as well as inside the Dodgers ballpark.

***Rancho Palos Verdes to Torrance Memorial Hospital Reference Mission***

Table 69 displays the specifications for the Rancho Palos Verdes to Torrance Memorial Hospital reference mission. Rancho Palos Verdes is an affluent suburban town in southern Los Angeles County situated on the Palos Verdes Peninsula. The resident community must cross over the Palos Verdes Hills and off the peninsula in order to reach major healthcare centers. This community therefore experiences longer distance and travel time to medical care than many other areas in the L.A. basin. The mission destination is Torrance Memorial Hospital.

The nearest currently available helipad to the origin point in the Rancho Palos Verdes neighborhood is a private surface helipad on the southern bluff of the peninsula, roughly 3.3 miles away. The mission destination point is the Torrance Memorial Hospital medical helicopter landing facility located on the north edge of Torrance Airport.

Table 69. Rancho Palos Verdes to Torrance Memorial Hospital reference mission specifications.

|                             |   |                   |                       |
|-----------------------------|---|-------------------|-----------------------|
| <b>Type:</b>                | Intra-City, Emergency   |                   |                       |
| <b>Origin:</b>              | 30692 Calle De Suenos, Rancho Palos Verdes, CA 90275                  |                   |                       |
| <b>2016 Origin Helipad:</b> | Private Helipad: Prickly Pear Trail, Rancho Palos Verdes, CA 90275    |                   |                       |
| <b>Destination:</b>         | Torrance Memorial Hospital, 3330 Lomita Boulevard, Torrance, CA 90505 |                   |                       |
| <b>Destination Helipad:</b> | on-site   |                   |                       |
| <b>Driving Distance:</b>    | 8.5   | mi primary ground | 8 mi secondary ground |
| <b>2016 ODM Distance:</b>   | 3.3   | mi to helipad     | 5.6 mi LOS flight     |

Table 70 presents the ground transportation study for the Rancho Palos Verdes to Torrance Memorial Hospital reference mission. Figure 104 presents the transportation study travel time and average speed distribution. This mission presents the most flat (stable) travel time distribution of all the reference missions. This is possibly a result that this reference mission requires travel completely through suburban areas, and does not involve any highways. As a result, the influence of commuter congestion may be limited for this mission. The peak travel time at 3:00 PM is only five minutes greater, on average, than the minimum travel time at 6:00 AM.

Table 70. Rancho Palos Verdes to Torrance Memorial Hospital reference mission ground transportation study.

|                | Date      | Time  | Travel Time (minutes) |      |         |     | Avg. Speed (MPH) |
|----------------|-----------|-------|-----------------------|------|---------|-----|------------------|
|                |           |       | Low                   | High | Average | +/- |                  |
| <b>Inbound</b> | 5/17/2016 | 5:00  | 18                    | 18   | 18      | 0   | 28               |
|                | 5/17/2016 | 6:00  | 18                    | 18   | 18      | 0   | 28               |
|                | 5/17/2016 | 7:00  | 16                    | 22   | 19      | 3   | 27               |
|                | 5/17/2016 | 8:00  | 18                    | 24   | 21      | 3   | 24               |
|                | 5/17/2016 | 9:00  | 18                    | 24   | 21      | 3   | 24               |
|                | 5/17/2016 | 10:00 | 18                    | 24   | 21      | 3   | 24               |
|                | 5/17/2016 | 11:00 | 18                    | 24   | 21      | 3   | 24               |
|                | 5/17/2016 | 12:00 | 18                    | 24   | 21      | 3   | 24               |
|                | 5/17/2016 | 13:00 | 18                    | 24   | 21      | 3   | 24               |
|                | 5/17/2016 | 14:00 | 18                    | 24   | 21      | 3   | 24               |
|                | 5/17/2016 | 15:00 | 18                    | 28   | 23      | 5   | 22               |
|                | 5/17/2016 | 16:00 | 18                    | 26   | 22      | 4   | 23               |
|                | 5/17/2016 | 17:00 | 18                    | 26   | 22      | 4   | 23               |
|                | 5/17/2016 | 18:00 | 18                    | 24   | 21      | 3   | 24               |
|                | 5/17/2016 | 19:00 | 18                    | 22   | 20      | 2   | 26               |
| 5/17/2016      | 20:00     | 16    | 22                    | 19   | 3       | 27  |                  |

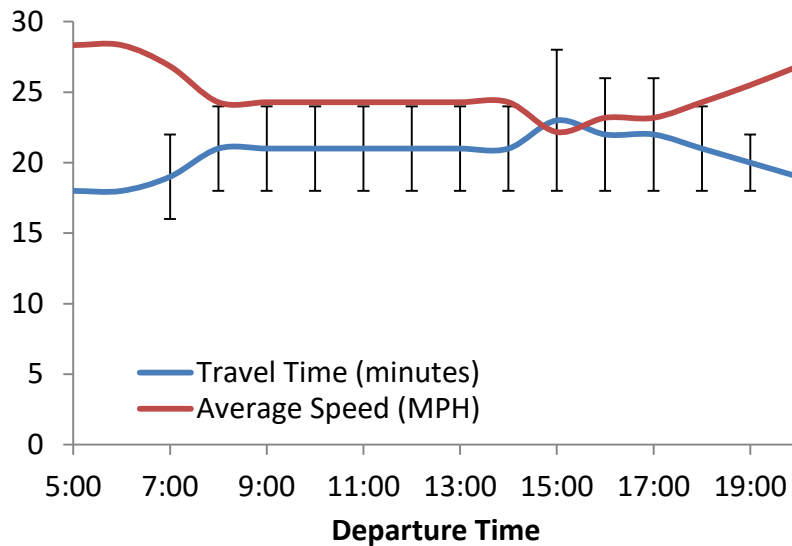


Figure 104. Rancho Palos Verdes to Torrance Memorial Hospital reference mission travel time and average speed distribution.

These characteristics suggest ODM aircraft services for medical missions such as this may not represent a significant market demand. The travel times to the nearest urgent care hospital are not large, and in this case are not heavily influenced by congestion. Furthermore, the current lack of

availability of landing facilities in suburban areas limits the potential convenience and time reductions possible through ODM aircraft services.

That said, ODM aircraft medical services could possibly capture greater market demand with consideration of a few other factors. First of all, with access to more rapid and less congested travel through ODM aircraft services, individuals may desire to travel to hospitals in farther away areas in order to see a specific doctor or clinic. Secondly, for situations where an individual is unable to drive a patient to the hospital and requires medical transportation, ODM aircraft services may be faster than standard ambulances if on-site landings were possible. Although the Rancho Palos Verdes reference mission is only 8.5 miles driving distance, the ambulance round trip distance from the hospital is 17 miles and an aircraft may have a significant round trip time reduction. With these considerations, ODM aircraft services for medical purposes should be considered as a potential early adopter market.

### ***San Marino to Palm Springs Reference Mission***

Table 71 displays the specifications for the San Marino to Palm Springs reference mission. A mission origin point was selected within the San Marino community where average home valuations were in the multiple millions. The mission destination is the Mission Hills Country Club which is a popular golf and tennis destination in Rancho Mirage, just south of Palm Springs.

The nearest currently available helipad to the origin point in San Marino is an EHLF located on a high-rise in downtown Pasadena, 2.1 miles north of the origin point. The current destination landing facility is the Palm Springs Airport which is 6.3 miles north west of the Mission Hills Country Club.

Table 71. San Marino to Palm Springs reference mission specifications.

|                             |  |                   |                         |
|-----------------------------|--|-------------------|-------------------------|
| <b>Type:</b>                | Recreation   |                   |                         |
| <b>Origin:</b>              | 1540 Oak Grove Ave, San Marino, CA 91108                                 |                   |                         |
| <b>2016 Origin Helipad:</b> | EHLF: 55 S Lake Ave, Pasadena, CA 91101                                  |                   |                         |
| <b>Destination:</b>         | Country Club: 34600 Mission Hills Dr, Rancho Mirage, CA 92270            |                   |                         |
| <b>Destination Helipad:</b> | Palm Springs Airport: 3400 E Tahquitz Canyon Way, Palm Springs, CA 92262 |                   |                         |
| <b>Driving Distance:</b>    | 116  | mi primary ground | 145 mi secondary ground |
| <b>2016 ODM Distance:</b>   | 2.1  | mi to helipad     | 96 mi LOS flight        |

Table 72 presents the ground transportation study for the San Marino to Palm Springs reference mission. Figure 105 presents the transportation study travel time and average speed distribution. This reference mission displays a single peak congestion mode during the evening rush hour. Since the route passes through San Bernardino, it can be seen that the peak congestion period from this mission corresponds with that from the San Bernardino to Glendale mission in Figure 96.

Table 72. San Marino to Palm Springs reference mission ground transportation study.

|                | Date      | Time  | Travel Time (minutes) |      |         |     | Avg. Speed (MPH) |
|----------------|-----------|-------|-----------------------|------|---------|-----|------------------|
|                |           |       | Low                   | High | Average | +/- |                  |
| <b>Inbound</b> | 5/17/2016 | 5:00  | 110                   | 140  | 125     | 15  | 56               |
|                | 5/17/2016 | 6:00  | 110                   | 140  | 125     | 15  | 56               |
|                | 5/17/2016 | 7:00  | 110                   | 140  | 125     | 15  | 56               |
|                | 5/17/2016 | 8:00  | 110                   | 140  | 125     | 15  | 56               |
|                | 5/17/2016 | 9:00  | 110                   | 140  | 125     | 15  | 56               |
|                | 5/17/2016 | 10:00 | 110                   | 140  | 125     | 15  | 56               |
|                | 5/17/2016 | 11:00 | 110                   | 140  | 125     | 15  | 56               |
|                | 5/17/2016 | 12:00 | 110                   | 140  | 125     | 15  | 56               |
|                | 5/17/2016 | 13:00 | 110                   | 140  | 125     | 15  | 56               |
|                | 5/17/2016 | 14:00 | 110                   | 150  | 130     | 20  | 54               |
|                | 5/17/2016 | 15:00 | 130                   | 220  | 175     | 45  | 40               |
|                | 5/17/2016 | 16:00 | 140                   | 230  | 185     | 45  | 38               |
|                | 5/17/2016 | 17:00 | 140                   | 200  | 170     | 30  | 41               |
|                | 5/17/2016 | 18:00 | 130                   | 170  | 150     | 20  | 46               |
|                | 5/17/2016 | 19:00 | 110                   | 150  | 130     | 20  | 54               |
| 5/17/2016      | 20:00     | 110   | 140                   | 125  | 15      | 56  |                  |

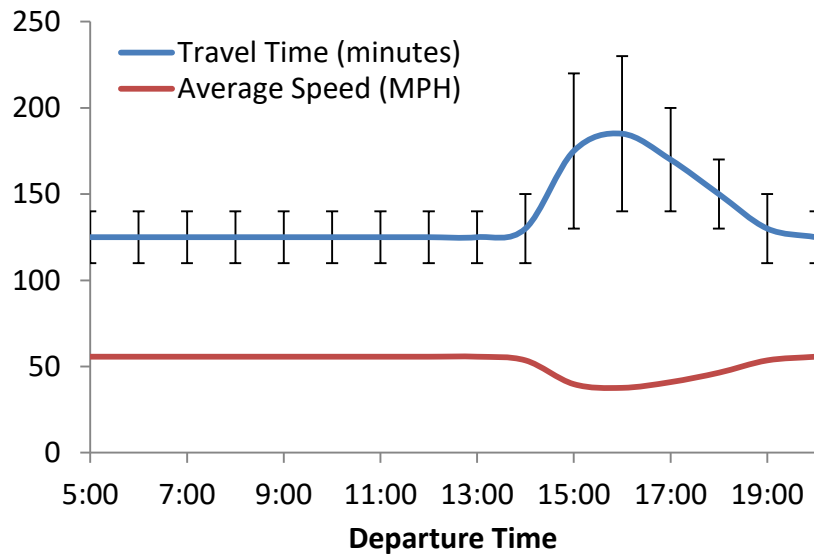


Figure 105. San Marino to Palm Springs reference mission travel time and average speed distribution.

Individuals travelling to Palm Springs from San Marino, or the general Los Angeles area, face two hours of travel to cover the over 100 mile trip. Those leaving after work are likely to encounter congestion increasing their trip to over three hours of travel. In either case, ODM Aviation has the potential to dramatically reduced travel time and avoid potential congestion on the roadways.

**Random Reference Mission 1: San Bernardino to Perris**

Table 73 displays the specifications for the San Bernardino to Perris randomly defined reference mission. The nearest existing takeoff infrastructure to the origin point is the San Bernardino International Airport, located two miles east. The nearest landing infrastructure to the destination is a private airport that is a ten mile drive away.

Table 73. San Bernardino to Perris reference mission specifications.

|                             |  |                   |                          |
|-----------------------------|--|-------------------|--------------------------|
| <b>Origin:</b>              | 24313 4 <sup>th</sup> St. San Bernardino, CA 92410 |                   |                          |
| <b>2016 Origin Helipad:</b> | San Bernardino International Airport               |                   |                          |
| <b>Destination:</b>         | 21131 Elmwood St, Perris, CA 92570                 |                   |                          |
| <b>Destination Helipad:</b> | Perris Valley Airport (10 miles from destination)  |                   |                          |
| <b>Driving Distance:</b>    | 26   | mi primary ground | 29.6 mi secondary ground |
| <b>2016 ODM Distance:</b>   | 2  | mi to helipad     | 22 mi LOS flight         |

Table 74 presents the ground transportation study for the San Bernardino to Perris reference mission. Ground transportation commuting times were predicted by the Google Maps™ mapping service. Like the point-to-point reference mission, the direction of travel for this control mission was assumed to be constant.

Table 74. Malibu to Century City reference mission ground transportation study.

|                 | Date      | Time  | Travel Time (minutes) |      |         |     | Avg. Speed (MPH) |
|-----------------|-----------|-------|-----------------------|------|---------|-----|------------------|
|                 |           |       | Low                   | High | Average | +/- |                  |
| <b>Inbound</b>  | 6/14/2016 | 5:00  | 28                    | 40   | 34      | 6   | 46               |
|                 | 6/14/2016 | 6:00  | 28                    | 40   | 34      | 6   | 46               |
|                 | 6/14/2016 | 7:00  | 30                    | 50   | 40      | 10  | 39               |
|                 | 6/14/2016 | 8:00  | 30                    | 45   | 37.5    | 7.5 | 42               |
|                 | 6/14/2016 | 9:00  | 28                    | 40   | 34      | 6   | 46               |
|                 | 6/14/2016 | 10:00 | 28                    | 40   | 34      | 6   | 46               |
|                 | 6/14/2016 | 11:00 | 28                    | 40   | 34      | 6   | 46               |
| <b>Outbound</b> | 6/14/2016 | 12:00 | 30                    | 45   | 37.5    | 7.5 | 42               |
|                 | 6/14/2016 | 13:00 | 30                    | 45   | 37.5    | 7.5 | 42               |
|                 | 6/14/2016 | 14:00 | 30                    | 50   | 40      | 10  | 39               |
|                 | 6/14/2016 | 15:00 | 35                    | 55   | 45      | 10  | 35               |
|                 | 6/14/2016 | 16:00 | 40                    | 70   | 55      | 15  | 28               |
|                 | 6/14/2016 | 17:00 | 40                    | 70   | 55      | 15  | 28               |
|                 | 6/14/2016 | 18:00 | 35                    | 55   | 45      | 10  | 35               |
| 6/14/2016       | 19:00     | 28    | 40                    | 34   | 6       | 46  |                  |
| 6/14/2016       | 20:00     | 30    | 40                    | 35   | 5       | 45  |                  |

Figure 106 presents a time diagram of the transportation study travel time and average speed distribution. The diagram displays a relatively rapid rate of travel with a period of congestion corresponding to the evening rush hour.



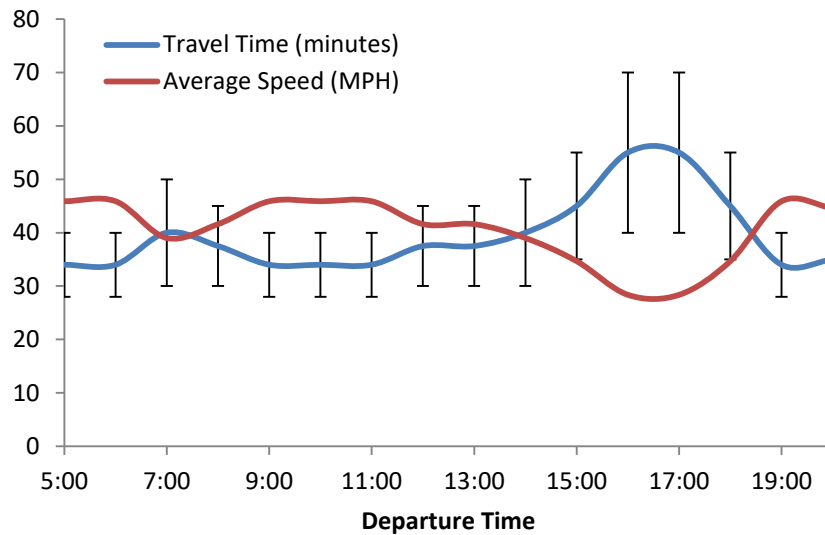


Figure 106. San Bernardino to Perris reference mission travel time and average speed distribution.

### ***Random Reference Mission 2: Arleta to Corona***

Table 75 displays the specifications for the Arleta to Corona randomly defined reference mission. The nearest existing takeoff infrastructure to the origin point is the Whiteman airport, located a little over two miles east of the origin point. The nearest landing infrastructure to the destination is the Corona airport located eight miles north west of the destination point.

Table 75. Arleta to Corona reference mission specifications.

|                             |  |                   |                        |
|-----------------------------|--|-------------------|------------------------|
| <b>Origin:</b>              | 9688 Elon Ave, Arleta, CA 91331            |                   |                        |
| <b>2016 Origin Helipad:</b> | Whiteman Airport                           |                   |                        |
| <b>Destination:</b>         | 19914 Temescal Canyon Rd, Corona, CA 92881 |                   |                        |
| <b>Destination Helipad:</b> | Corona Airport (8 miles from destination)  |                   |                        |
| <b>Driving Distance:</b>    | 71   | mi primary ground | 77 mi secondary ground |
| <b>2016 ODM Distance:</b>   | 2.2  | mi to helipad     | 52 mi LOS flight       |

Table 76 presents the ground transportation study for the Arleta to Corona reference mission. Figure 107 presents a time diagram of the transportation study travel time and average speed distribution. The diagram displays a slight bimodal congestion pattern with the evening ground congestion more significant than congestion in the morning.

Table 76. Arleta to Corona reference mission ground transportation study.

|          |           | Travel Time (minutes) |      |         |       | Avg. Speed (MPH) |    |
|----------|-----------|-----------------------|------|---------|-------|------------------|----|
| Date     | Time      | Low                   | High | Average | +/-   |                  |    |
| Inbound  | 6/14/2016 | 5:00                  | 75   | 100     | 87.5  | 12.5             | 48 |
|          | 6/14/2016 | 6:00                  | 75   | 110     | 92.5  | 17.5             | 46 |
|          | 6/14/2016 | 7:00                  | 85   | 140     | 112.5 | 27.5             | 38 |
|          | 6/14/2016 | 8:00                  | 85   | 140     | 112.5 | 27.5             | 38 |
|          | 6/14/2016 | 9:00                  | 75   | 110     | 92.5  | 17.5             | 46 |
|          | 6/14/2016 | 10:00                 | 70   | 100     | 85    | 15               | 50 |
|          | 6/14/2016 | 11:00                 | 70   | 100     | 85    | 15               | 50 |
|          | 6/14/2016 | 12:00                 | 75   | 110     | 92.5  | 17.5             | 46 |
| Outbound | 6/14/2016 | 13:00                 | 80   | 110     | 95    | 15               | 45 |
|          | 6/14/2016 | 14:00                 | 85   | 140     | 112.5 | 27.5             | 38 |
|          | 6/14/2016 | 15:00                 | 100  | 190     | 145   | 45               | 29 |
|          | 6/14/2016 | 16:00                 | 110  | 180     | 145   | 35               | 29 |
|          | 6/14/2016 | 17:00                 | 100  | 160     | 130   | 30               | 33 |
|          | 6/14/2016 | 18:00                 | 90   | 130     | 110   | 20               | 39 |
|          | 6/14/2016 | 19:00                 | 75   | 100     | 87.5  | 12.5             | 48 |
|          | 6/14/2016 | 20:00                 | 70   | 90      | 80    | 10               | 53 |

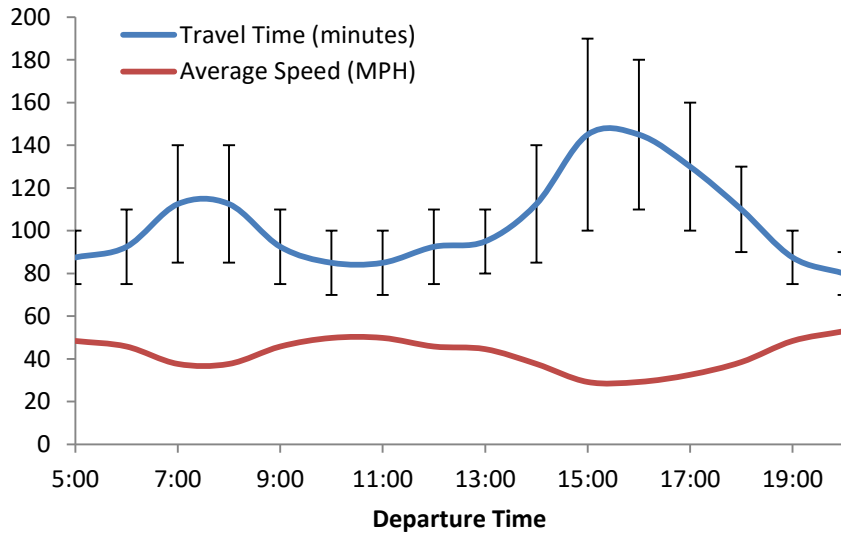


Figure 107. Arleta to Corona reference mission travel time and average speed distribution.

### ***Random Reference Mission 3: Altadena to Culver City***

Table 77 displays the specifications for the Altadena to Culver City randomly defined reference mission. The nearest existing helipad to the origin point is at the NASA Jet Propulsion Laboratory, located three miles west of the origin point. The nearest landing infrastructure to the destination is the Hughes Corporation heliport located a little over 3 miles from the destination.

Table 77. Altadena to Culver City reference mission specifications.

|                             |  |                   |                        |
|-----------------------------|--|-------------------|------------------------|
| <b>Origin:</b>              | 3599 Loma View Dr, Altadena, CA 91001                |                   |                        |
| <b>2016 Origin Helipad:</b> | NASA Jet Propulsion Laboratory                       |                   |                        |
| <b>Destination:</b>         | 11878 Port Road, Culver City                         |                   |                        |
| <b>Destination Helipad:</b> | Hughes Corporate heliport (3 miles from destination) |                   |                        |
| <b>Driving Distance:</b>    | 30   | mi primary ground | 34 mi secondary ground |
| <b>2016 ODM Distance:</b>   | 3.3  | mi to helipad     | 21 mi LOS flight       |

Table 78 presents the ground transportation study for the Arleta to Corona reference mission.

Table 78. Altadena to Culver City reference mission ground transportation study.

|                 |             | <b>Travel Time (minutes)</b> |             |                |            | <b>Avg. Speed (MPH)</b> |    |
|-----------------|-------------|------------------------------|-------------|----------------|------------|-------------------------|----|
| <b>Date</b>     | <b>Time</b> | <b>Low</b>                   | <b>High</b> | <b>Average</b> | <b>+/-</b> |                         |    |
| <b>Inbound</b>  | 6/14/2016   | 5:00                         | 40          | 50             | 45         | 5                       | 39 |
|                 | 6/14/2016   | 6:00                         | 55          | 85             | 70         | 15                      | 25 |
|                 | 6/14/2016   | 7:00                         | 70          | 130            | 100        | 30                      | 18 |
|                 | 6/14/2016   | 8:00                         | 75          | 130            | 102.5      | 27.5                    | 17 |
|                 | 6/14/2016   | 9:00                         | 65          | 110            | 87.5       | 22.5                    | 20 |
|                 | 6/14/2016   | 10:00                        | 55          | 85             | 70         | 15                      | 25 |
|                 | 6/14/2016   | 11:00                        | 50          | 75             | 62.5       | 12.5                    | 28 |
|                 | 6/14/2016   | 12:00                        | 45          | 70             | 57.5       | 12.5                    | 31 |
| <b>Outbound</b> | 6/14/2016   | 13:00                        | 45          | 70             | 57.5       | 12.5                    | 31 |
|                 | 6/14/2016   | 14:00                        | 50          | 80             | 65         | 15                      | 27 |
|                 | 6/14/2016   | 15:00                        | 55          | 90             | 72.5       | 17.5                    | 24 |
|                 | 6/14/2016   | 16:00                        | 60          | 100            | 80         | 20                      | 22 |
|                 | 6/14/2016   | 17:00                        | 65          | 120            | 92.5       | 27.5                    | 19 |
|                 | 6/14/2016   | 18:00                        | 60          | 100            | 80         | 20                      | 22 |
|                 | 6/14/2016   | 19:00                        | 45          | 65             | 55         | 10                      | 32 |
|                 | 6/14/2016   | 20:00                        | 40          | 55             | 47.5       | 7.5                     | 37 |

Figure 108 presents a time diagram of the transportation study travel time and average speed distribution. The diagram displays bimodal congestion pattern with significant variance throughout the day that especially pronounced during the peak congestion periods.

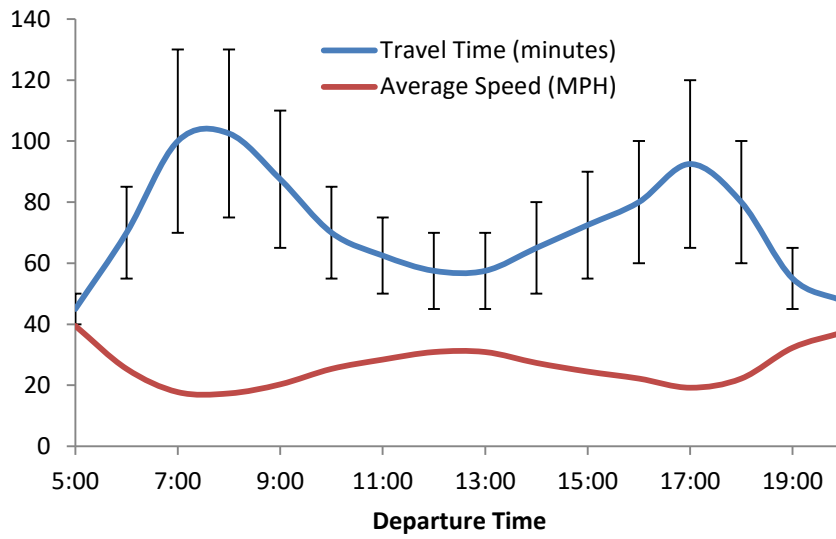


Figure 108. Altadena to Culver City reference mission travel time and average speed distribution.

## **Appendix B: Reference Mission ConOps Review**

This appendix introduces the mission ConOps review of the San Diego City Center to Los Angeles City Center and the Beverly Hills Hotel to Los Angeles International Airport reference missions. These missions were not included in Section 5.2 in an effort to reduce length, and the review of all twelve reference missions was not presented in this appendix for the same reason. These two additional reference mission reviews were selected to provide examples of a long distance and short distance point-to-point mission, respectively. Taken together, the three ConOps reviews presented in the main body of the thesis and this appendix introduce each of the 20 ODM Aviation operational challenges identified.

### **San Diego City Center to Los Angeles City Center**

#### **ConOps Step 1: Customer Submits a Travel Request**

No operational challenge identified for any of the reference missions.

#### **ConOps Step 2: Aircraft Routed to the Nearest TOLA**

Figure 109 displays the existing TOLA infrastructure surrounding the San Diego origin point. The origin point at One America Plaza does not have an on-site helipad facility. Within two blocks (0.1 nmi) of the origin there currently exist five helipads, all residing to the east. Three of the helipads are EHLFs, and two are for private operations.

The Emerald Plaza heliport was selected as the primary TOLA for this reference mission as it is currently promoted as a private landing facility and therefore could readily be made available for ODM operations. If ODM operations were to require additional facilities to meet demand, then there is a second EHLF helipad on Emerald Plaza that may be potentially converted to support operations. Nearby EHLF helipads on the buildings immediately north east and south east of One America Plaza could also be considered as potential additional ODM TOLAs.

The high density of rooftop TOLAs in the San Diego city center may allow for numerous ODM aircraft to be staged on-site. Furthermore, if a centralized staging facility was needed, there are multiple public airports within fifteen miles (two within five miles) of the origin point that could be used for this purpose. TOLA congestion is not likely to be a challenge for low to medium density ODM networks as customers may be distributed among the numerous TOLAs in the area to increase local area throughput. However, some sort of priority system would still need to be developed to handle which operation has access to a specific TOLA.



Figure 109. Current TOLA infrastructure in the San Diego City Center.  
 © 2016 Google. © 2016 INEGI.

**ConOps Step 3: Customer Takes Ground Transportation from the Origin to the TOLA**

As numerous TOLAs currently exist well within the quarter mile acceptable walking distance for customers, first mile ground transportation is not necessary for the San Diego reference mission.

**ConOps Step 4: Customer Arrives the TOLA and is Prepared for Takeoff**

The primary TOLA selected for this mission was on the roof of a Westin Hotel in the Emerald Plaza building. While hotel lobbies are in general easily accessible to the public, elevators to the upper floors and especially roof access are not typically open to the public. Therefore, customer access to the TOLA may be a potential operational challenge for this mission and require changes to hotel infrastructure or a customer escort.

Due to the rooftop nature of the helipad, it was anticipated the security of the facility will be less of a challenge than the surface-level Malibu helipad. Providing appropriate safety for customers entering the helipad will still be necessary.

Finally, the turn-time for the aircraft remained a potential challenge for this mission as well as all other reference missions.

**ConOps Step 5: Flight Segment**

To develop flight profiles for the flight segment of each reference mission, studies were conducted concerning the airspaces, aircraft traffic and ground population densities. A variety of flight profiles were developed for each reference mission that expressed different potentially desirable

features. The flight profiles were reviewed to identify potential ODM Aviation operational challenges that may arise from the flight segment step of the ConOps.

### *San Diego to Los Angeles Airspace Considerations*

Potential routes from San Diego to Los Angeles are much longer than the Malibu to Century City reference mission and interact with many more controlled airspaces and areas of congestion. Flight near, under or through these airspaces requires various ATC clearances, equipment or procedures as summarized in Appendix C. The relevant airspaces for this reference mission are discussed below, neglecting those previously introduced for the Malibu reference mission. The Camp Pendleton Marine Corps Air Station restricted airspace is an especially interesting complication of this flight.

*San Diego Class B airspace:* The San Diego (SAN) Class B airspace reaches from the surface to 3300 ft MSL in the area directly over the origin point and Emerald Plaza helipad. Class E airspace spans the area between 3300 ft and 4700 ft at which point another shelf of the SAN Class B airspace begins reaching from 4700 ft to 10,000 ft MSL. A VFR corridor passes through the Class G airspace between these two shelves west of the origin point and runs north overtop the SAN runway. The SAN Class B airspace is a complex network of two interacting IFR networks extending from the San Diego International Airport and the Marine Corps Air Station Miramar. Entrance into the SAN airspace (before takeoff or on approach for landing) requires ATC clearance and a given routing must be followed. Flight within the Class B airspace is limited to 250 kts, and flight beneath any Class B airspace shelf is limited to 200 kts.

*John Wayne Airport Class C airspace:* Roughly 29 nmi south east of the Los Angeles city center is John Wayne airport. This airport is immediately surrounded by Class C airspace extending from the surface to 4400 ft MSL out to a five nautical mile radius, and then an outer layer of airspace spanning various altitudes in different sections from 1500 to 5400 ft MSL. Aircraft entering Class C airspace must establish and maintain two-way radio communications. Flight within four nautical miles of the John Wayne airport below 2,500 ft AGL is limited to 200 kts.

*Class D airspace:* Flights between San Diego and Los Angeles have the possibility of encountering numerous Class D airspaces depending upon the route taken. These include Class D airspace around Air Station North Island, Montgomery Field, Gillespie Field, Ramona Airport, McClellan-Palomar Airport, Air Station Camp Pendleton, Los Alamitos Army Airfield, Long Beach Airport, Zamperini Field, Fullerton Airport, and Hawthorne Airport. Flight into Class D airspace requires the pilot to establish and maintain two-way radio contact and respect weather minimums. Some of these Class D airspaces have limited active hours outside of which they revert to Class E or Class G airspace.

*Camp Pendleton Marine Corps Air Station Restricted Airspace:* There are four restricted airspaces associated with Camp Pendleton. The airspace containing the coastline is active between 6:00 AM and 11:59 PM local time every day from the surface to 2,000 ft MSL. An inland airspace is active for the same period reaching from the surface to 15,000 ft MSL [203]. Two other more expansive restricted airspaces may be activated infrequently through NOTAM issuance. Due to these airspaces, it is likely that most ODM operations may be routed offshore or over top of the coastal restricted airspace.

## Air Traffic Interaction

This section reviews potential interactions ODM aircraft may have with other aircraft through the course of the mission.

**Helicopter Operations:** There are no established FAA helicopter routes within San Diego. It is therefore likely that local helicopter pilots operate primarily along the routes indicated in the VFR Flyway Planning Chart as shown in Figure 110. An ODM aircraft entering the Los Angeles area from the south along the coast is likely to encounter two helicopter VFR routes after passing Camp Pendleton: the coastal route, and the east San Diego freeway route. Once reaching the L.A. basin, three helicopter routes extend from the Long Beach southern shore north towards Los Angeles. In addition, there are a variety of transition routes extending outward from the Long Beach airport, and Zamperini Field is a common helicopter training and flight test ground for Robinson Helicopter. Over 20 helicopter pads are located in Long Beach, and dozens of helicopter facilities are in or immediately around the Los Angeles city center.

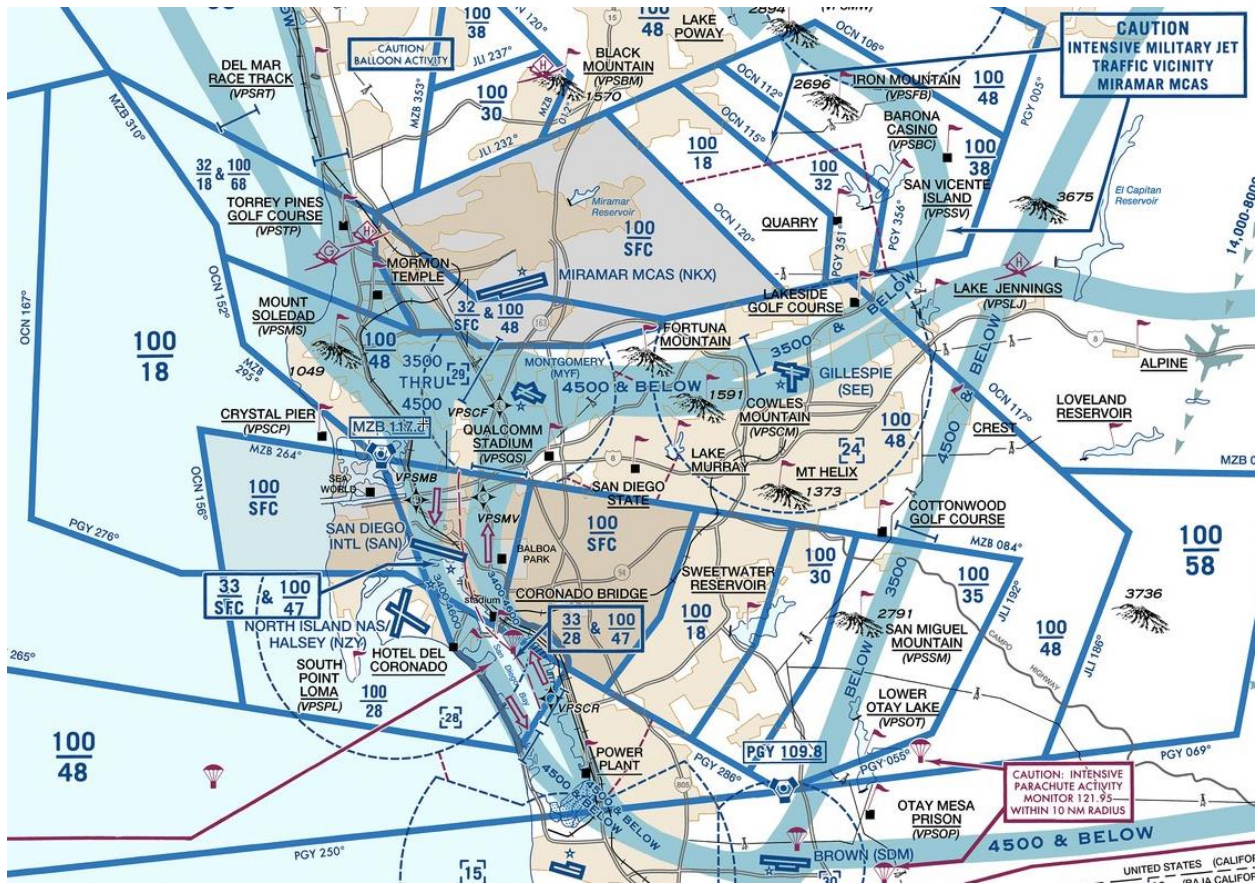


Figure 110. San Diego VFR Flyway Planning Chart.

**Fixed Wing Aircraft:** ODM aircraft departing from San Diego and entering into Los Angeles may potentially encounter congested air traffic. However, the airspace north of McClellan-Palomar Airport and south of John Wayne Airport is likely to be less congested with low altitude operations occurring primarily under VFR.



Departing from San Diego, ODM aircraft may encounter significant VFR traffic in the San Diego International Airport VFR Corridor. As visible in Figure 110, the VFR corridor is the primary route through the Class B airspace for VFR aircraft. If ODM operations wish to enter the Class B airspace, they may encounter significant commercial aircraft traffic entering and departing San Diego or Miramar. Extending up the coastline are victor airways 23, 363 and 597 which carry some IFR arrivals and departures in the San Diego area. If high density ODM aviation operations become a reality, then coordination of flights with the approach and departure paths to the multiple Class D airports beneath the San Diego Class B airspace may also be necessary.

ODM flights entering Los Angeles from the south will cross over two IFR arrival routes and the approach and departure paths for multiple airports. There are three VFR transition routes, plus the L.A. special rules flight area extending south to north in the L.A. basin and over LAX where ODM aircraft are likely to encounter VFR traffic.

#### Ground Population Noise Exposure

The coastal region from San Diego to Los Angeles is one of the most densely populated in the United States, except for the area surrounding Camp Pendleton which is rather sparsely populated. Many of the United States' most wealthy residential areas also lay along this stretch of coastline. Routing flights significantly inland may initially reduce population exposure around San Diego, however Riverside and San Bernardino counties east of Los Angeles are also densely populated. Shifting flights west over the Pacific Ocean may also reduce population exposure to aircraft noise from ODM operations. Figure 111 displays a population density map for the area between San Diego and Los Angeles.

[Intentionally Left Blank]

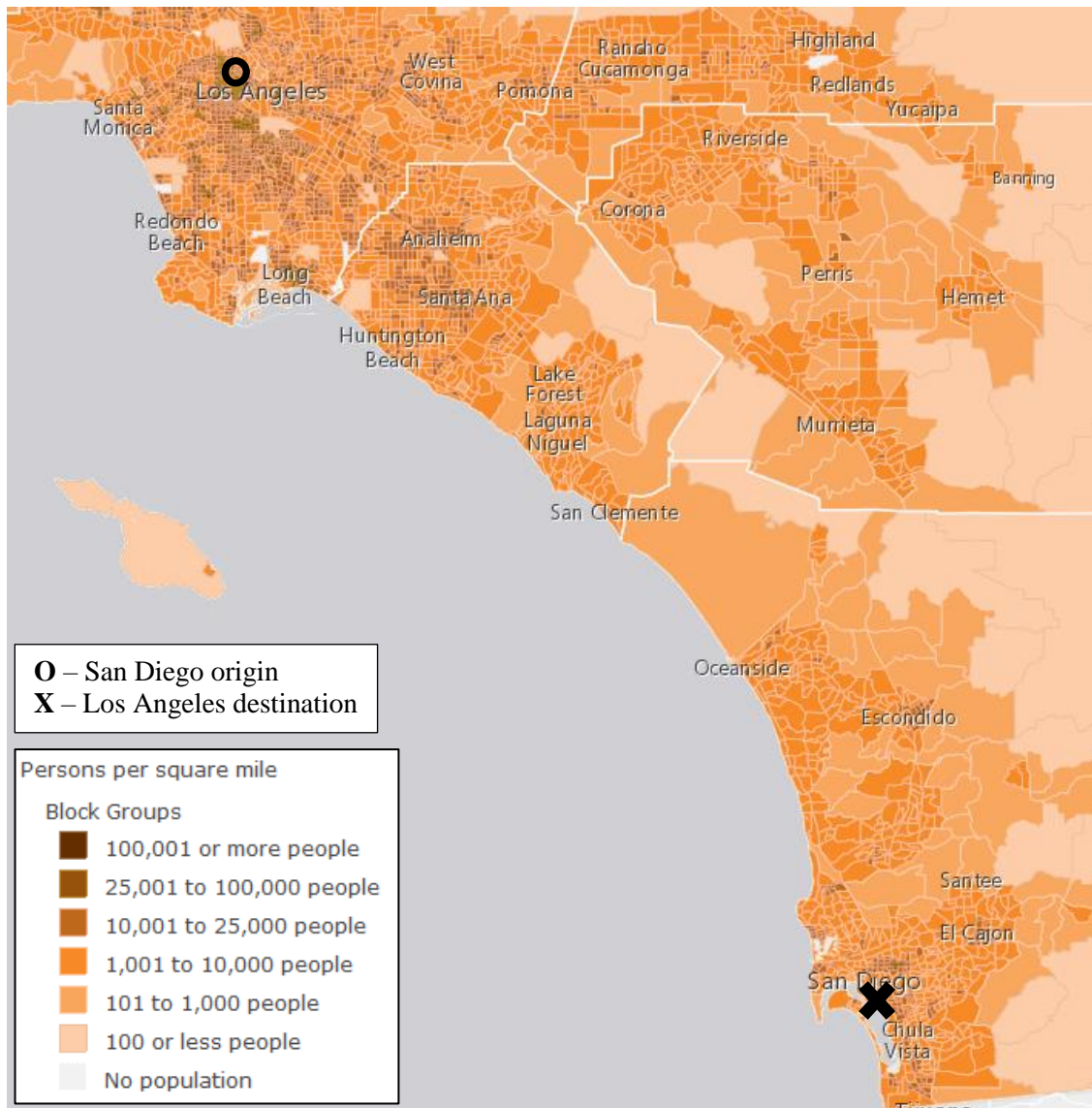


Figure 111. 2012 population density of census block groups between San Diego and Los Angeles  
*USA\_Population\_Density map © 2013 Esri, retrieved from www.arcgis.com.*

Mission Flight Profile Development

A variety of potential flight profiles were developed to meet the needs of the San Diego to Los Angeles reference mission. All flights require entry into the San Diego Class B airspace upon takeoff from the Emerald Plaza helipad and must request routing from ATC to operate in and ultimately exit the airspace. This analysis assumed that ODM flight paths passing north over San Diego International Airport were required to rise to the VFR corridor to avoid arrival and departing flights, while ODM flight paths passing south or west out of San Diego were routed out of the Class B airspace at lower altitudes.

Four mission flight profiles were developed that represented approaches to meet various potential requirements and flight restrictions. Figure 112 displays an overview of the full flight profiles.



Figure 112. Potential flight paths from San Diego City Center to Los Angeles City Center.  
 © 2016 Google. Map Data: USGS, LDEO-Columbia, NSF, NOAA, SIO, U.S. Navy, NGA, GEBCO.

Figure 113 displays the first third of the potential routes in detail plotted on a FAA San Diego terminal area chart. Figure 114 displays the last third of the potential routes plotted on a FAA Los Angeles terminal area chart. The middle third of the flights was not plotted in detail as the flights were anticipated to occur at altitudes above Class D airspaces and avoid the Camp Pendleton restricted areas.

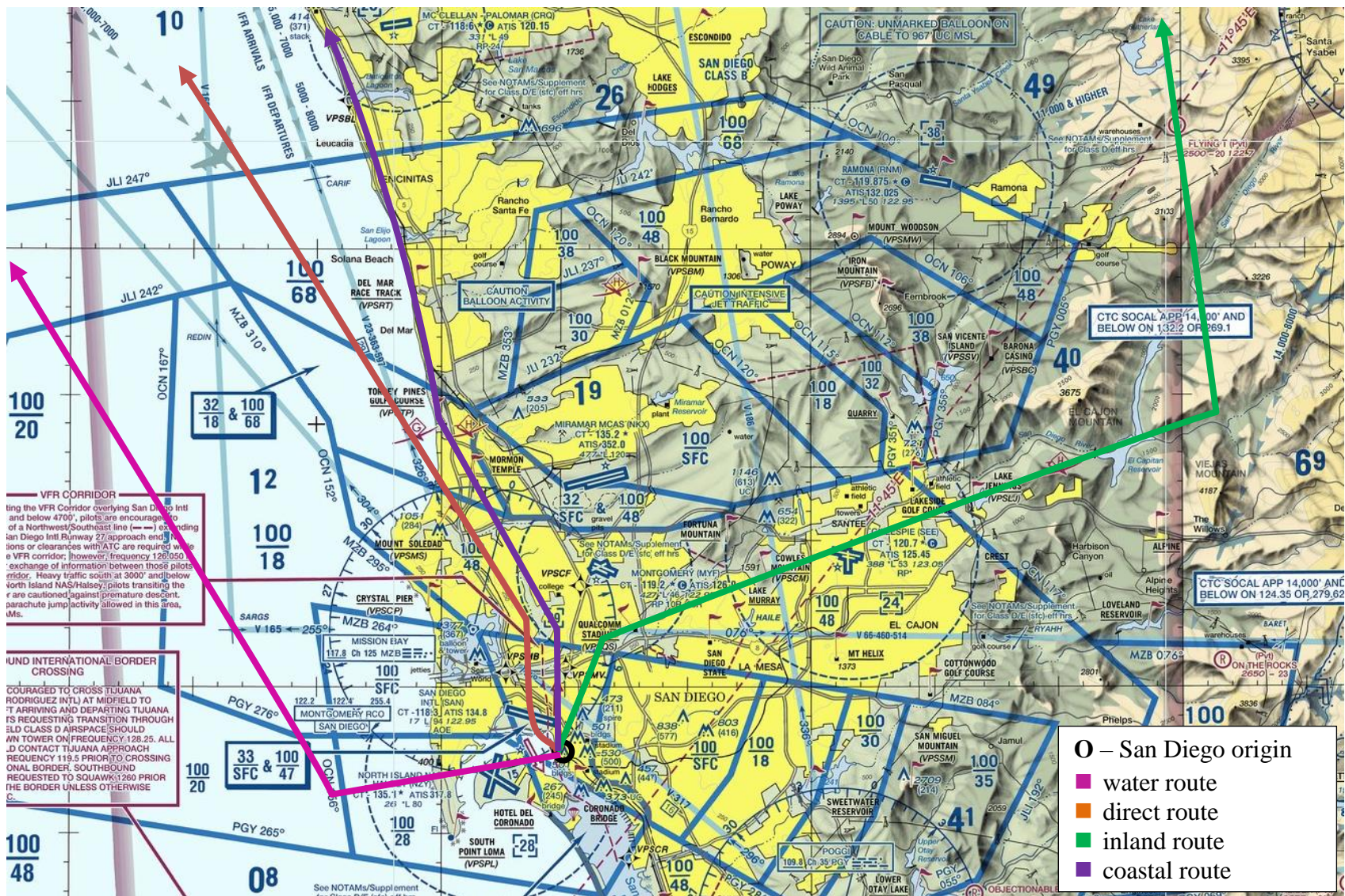


Figure 113. Route planning for San Diego departure towards Los Angeles.

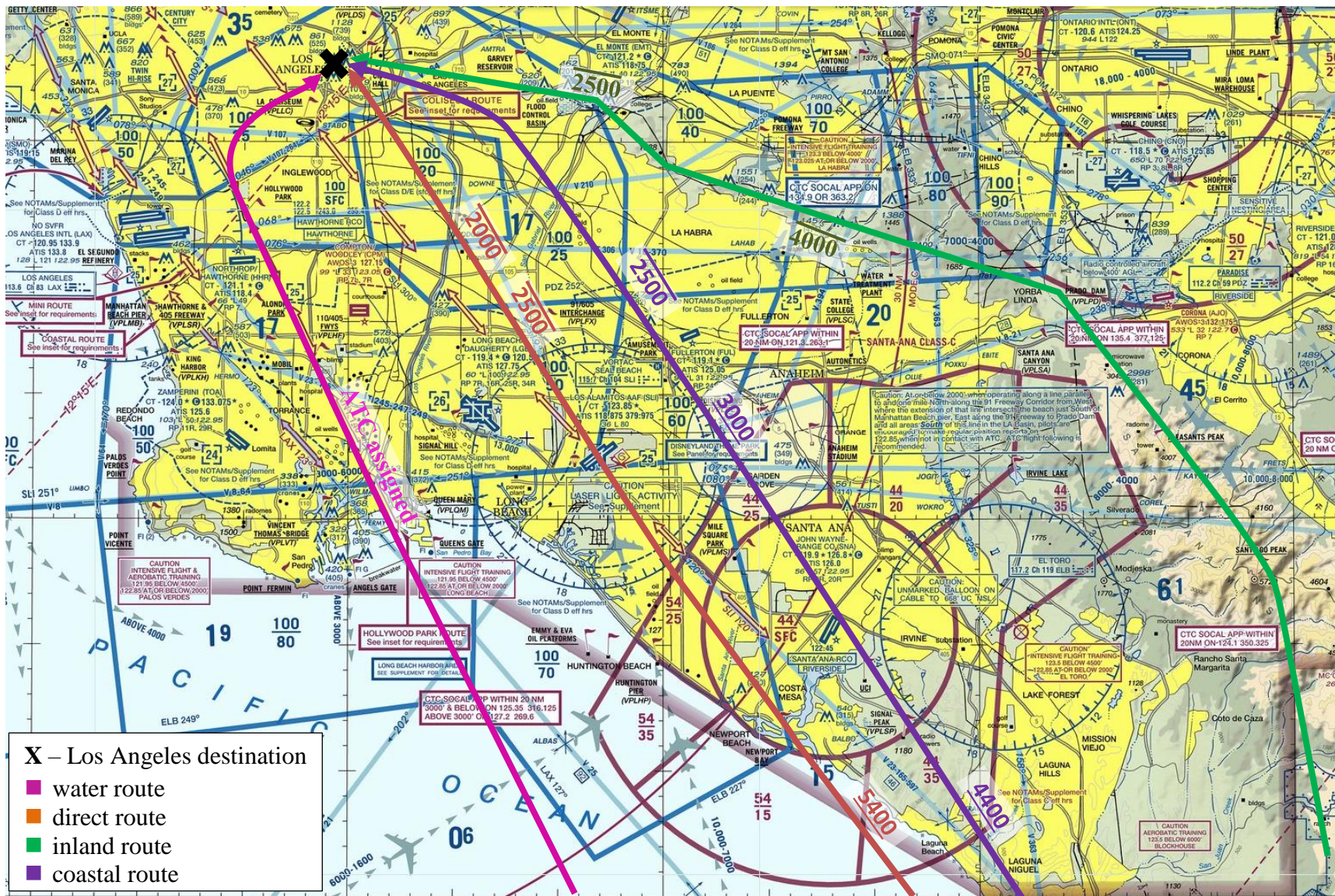


Figure 114. Route planning for Los Angeles arrival from San Diego.

1. Water Route: The water route seeks to maximize flight time over open water in order to reduce noise exposure on the ground. The route transits over the ocean as quickly as possible from San Diego and minimizes flight over Los Angeles subject to airspace constraints with LAX. The water route requires clearance to enter Los Angeles Class B airspace. The water route is slightly longer than the direct route but avoids approximately 14 nmi of flight over densely populated areas of L.A. and San Diego.

Flight Profile: Air Traffic Control must be contacted to provide a routing over the San Diego Bay towards the North Island Air Station. The route exits the Class B airspace and enters the North Island Class D airspace, following radio communication with the tower, at less than 2800 ft MSL. Upon exiting the North Island airspace and clearing the south western point of the surface-level Class B airspace, the route turns north-northwest towards Los Angeles and passes beneath an 1800 ft Class B airspace shelf over open ocean. The route continues towards Los Angeles gaining altitude as the Class B airspace floor rises. Once passing out from beneath the final Class B airspace floor, the flight may increase speed up to a maximum of 250 kts. The flight may proceed under VFR towards Long Beach and does not intersect any airspaces or high traffic areas for the cruise leg of the route.

On approach to Los Angeles the aircraft aligns with the Van Nuys 140 radial and request ATC clearance to enter the LAX Class B airspace and follow the Hollywood Park VFR route. ATC will assign an altitude and airspeed. After passing over Hollywood Park the aircraft may request permission from ATC to descend to 2500' MSL and exit class B airspace. When granted, the aircraft reduces speed to under 200 kts and proceeds to the final destination. The flight is completed by vertically landing at the destination helipad in Los Angeles.

2. Direct Route: The direct route proceeds north from San Diego over the Mission Valley and La Jolla before moving offshore on a direct path toward the destination in Los Angeles. The route passes over extensive portions of Los Angeles county, some at altitudes as low as 2000 ft MSL. Beyond exiting the San Diego Class B airspace, the route requires entrance into no other Class B or Class C airspace.

Flight Profile: This route follows a nearly direct line of sight between the San Diego origin point and Los Angeles destination. After gaining San Diego ATC clearance, the flight departs from Emerald City and follows ATC routing to cross north over the San Diego International Airport arrival route. The flight proceeds north along the VFR corridor and exits Class B airspace over the Mission Valley. If the flight is beneath 2900 ft MSL and the flight occurs between 6:00 AM and 9:00 PM then radio contact must be made to enter Montgomery Field Class D airspace; otherwise the flight has entered Class E airspace. The flight turns north-northwest and ascends to at least 3200 ft MSL to pass above another region of Class B airspace. The flight continues at no greater than 200 kts over the ocean and passes under the final shelf of Class B airspace.

The cruise leg of the path then continues at the chosen flight altitude on a path directly towards the Seal Beach VORTAC at 250 kts. This vector passes the flight over open ocean and west of the Camp Pendleton restricted airspaces. When approaching the John Wayne

Class C airspace, the flight should descend to less than 7000 ft, but greater than 5400 ft MSL to stay below an IFR approach path to Los Alamitos while remaining above the John Wayne airspace. The flight also must slow to 200 kts before passing beneath the overlying LAX Class B airspace.

Once clearing the John Wayne airspace, the flight descends to 2400 ft MSL before passing I-91. If the flight descends below 2500 ft before clearing Los Alamitos airspace, two way radio communication must be established with the control tower. The flight proceeds across highway 105 dropping another 500 feet in altitude to pass below the 2000 ft floor Class B airspace shelf. The route passes directly through the Long Beach Freeway helicopter VFR route as well as in the vicinity of four other helicopter routes, so potential congestion must be considered. The flight is completed by vertically landing at the destination helipad in Los Angeles.

3. Inland Route: The inland route avoids flight over open water and attempts to minimize flight over densely populated areas by flying along the Peninsular Range of mountains. The route is the longest of the proposed routes and does not involve flight in any Class B or C airspace except on departure from San Diego.

ConOps: The inland route begins in an identical fashion to the direct route, but diverges after crossing north of San Diego International Airport. At this point, the inland route turns east and passes over the Gillespie Field Class D airspace at at least 2400 ft, but less than the 4800 ft overlying Class B airspace floor. The flight continues east beyond the edge of the Class B airspace and may accelerate up to a velocity of 250 kts. The flight turns north after passing over the El Capitan reservoir and proceeds to follow the westward slope of the Peninsular Mountains.

At the Pauma Valley airport the route turns northwest towards the Pomona VORTAC. The route passes between the Riverside, Santa Ana and Ontario Class C airspaces and descends to 4500 ft MSL before passing over the Riverside Freeway. This area contains extensive VFR aircraft operations as well as a helicopter VFR route. The ODM aircraft speed must be reduced to 200 kts before passing under the overlying LAX class B airspace, and altitude should be reduced to 3500 ft before passing over the Orange Freeway. The route follows the descending mountain range until it connects with the Pomona Freeway. At this point the flight altitude is reduced to 2400 ft MSL and the route follows the Pomona Freeway helicopter VFR route into the L.A. City Center. The flight is completed by vertically landing at the destination helipad in Los Angeles.

4. Coastal Route: The coastal route avoids flight over open water by following the coastline between San Diego and Los Angeles. The route passes over multiple highly populated areas, however does so at altitude.

ConOps: The coastal route begins in an identical fashion to the direct route, but diverges once reaching the La Jolla Shores. At this point, the coastal route turns north and follows the coastline. After passing out from under the SAN Class D airspace, the flight may accelerate to a maximum velocity of 250 kts. If the flight occurs between 6:00 AM and

11:59 PM local time, it will pass overtop the Camp Pendleton R-2503A restricted airspace. However, if R-2503D is active the flight will either have to ascend to 11,000 ft MSL to fly over the top or route around.

The flight maintains at least 5500 ft MSL to pass overtop the Santa Ana Class C airspace and begins to descend immediately following passing over the airspace as described in the direct route. Note that the offset of the coastal route compared to the direct route will take the flight over the Disneyland prohibited airspace (which reaches up to 3000 ft MSL) as well as through Fullerton Class D airspace which is active from 7:00 AM until 9:00 PM and requires communication with the control tower during this time. The remainder of the coastal route follows the same flight profile as the direct route.

Table 30 provides a comparison of the total distance and duration of the four proposed San Diego to Los Angeles City Center mission flight profiles.

Table 79. San Diego to Los Angeles City Center flight profile comparisons.

| <b>Flight Profile</b> | <b>Distance (mi)</b> | <b>Duration (min)</b> |
|-----------------------|----------------------|-----------------------|
| Water Route           | 127.9                | 38                    |
| Direct Route          | 111.4                | 34                    |
| Inland Route          | 154.9                | 45                    |
| Coastal Route         | 115.3                | 36                    |

The direct route is the least distance and duration, however it requires substantial flight over open water and passes over significant portions of Los Angeles communities at flight altitudes below 2000 ft AGL. On high traffic density days this route could become crowded as well due to the proximity of this flight to numerous helicopter VFR routes in Los Angeles.

The water route is 15% longer than the direct route by distance, but only 11% longer by duration. Except for the low altitude flight segment in San Diego over the bay and air station, the route significantly reduces noise exposure compared to the other flight paths by operating for 71% of the distance over open water. Furthermore, the route utilizes an ATC VFR corridor that passes through the LAX Class B airspace at higher altitude than the other examined routes further reducing noise exposure on the ground. Challenges for this route include extended flight over water which may present new safety requirements and require different certifications for vehicle and operators. Additionally, the flight path requires LAX ATC clearance and permission to exit the Hollywood Park VFR corridor prematurely.

The inland route sacrifices flight distance and duration in an effort to mitigate noise, avoid air traffic congestion, and provide an alternative route around potential coastal weather or flight hazards. The inland route is 39% longer by distance and 32% longer by duration than the direct route. The route largely avoids overflight of densely populated areas. Once departing from the mountain range in Los Angeles, the inland route follows the Pomona freeway VFR helicopter route further reducing ground noise annoyance and integrating with local traffic.



Finally, the coastal route is similar to the direct route except it avoids flight over the open ocean. The route takes a minor distance and duration penalty to follow the coastline, but may avoid safety and certification costs necessary for flight over open water.

### Potential ODM Challenges from the Flight Segment

As seen in the development of the four potential flight profiles for the San Diego to Los Angeles reference mission, increased aircraft densities, aircraft noise and low altitude air traffic control are all potential operational challenges that appear again in this reference mission. This reference mission originates and concludes on elevated TOLAs which may reduce noise concerns, however the flight paths require extensive flight over densely populated urban and suburban areas.

#### **ConOps Step 6: Aircraft Arrives at Destination and Customer Disembarks**

The rooftop TOLA at the destination presents the same potential operational challenges identified in the Malibu to Century City reference mission.

#### **ConOps Step 7: Customer Takes Ground Transportation to Final Destination**

In the case of this reference mission, the final destination had an on-site TOLA and no additional “last mile” ground transportation was necessary.

#### **ConOps Step 8: Aircraft Recharges Batteries**

Unlike for daily commuter mission where the maximum throughput of the ODM network was of interest, for non-commute point-to-point missions it is typically the maximum number of missions per vehicle that is of interest. This is because point-to-point demand is typically non-directional and not concentrated on a single route or TOLA, but rather is distributed around the network. Therefore the key factor is the availability of an aircraft to meet demand as it arises. For full-electric aircraft, availability was found to primarily depend on battery recharging requirements.

To display the significance of this constraint, a nine hour operating day was considered for a single vehicle serving the San Diego to Los Angeles City Center route. It was assumed that the average one-way flight duration for an ODM aircraft from San Diego to Los Angeles was 38 minutes, 127 miles, and required roughly 55 minutes of charging after each flight (140 miles requires a 100% charge, therefore 127 miles requires a 91% charge). A 30% range reduction was applied to the aircraft to account for hovering and vertical ascent; this was consistent with the assumptions in the daily commute Malibu to Century City reference mission. It was also assumed that there was a demand queue at either node of the network so that as soon as the vehicle was prepared to fly, a customer was waiting. While this assumption may not have been realistic, it allowed for the estimation of an upper limit to the number of trips a single ODM aircraft could provide per day. Finally, the vehicle was assumed to recharge at the helipad it landed at without requiring transit to a different facility. This was also unlikely in actual operation as all helipads may not be outfit with charging stations and a charging vehicle could interrupt other operations.

Under these assumptions, a single ODM aircraft was capable of completing just under 6 one-way trips between San Diego and Los Angeles (in either directly) with ideally aligned customer demand over a nine hour period from 8:00 AM until 5:00 PM. Figure 115 displays the notional ConOps for an aircraft completing this reference mission, as well as for the utilization of the two helipads.

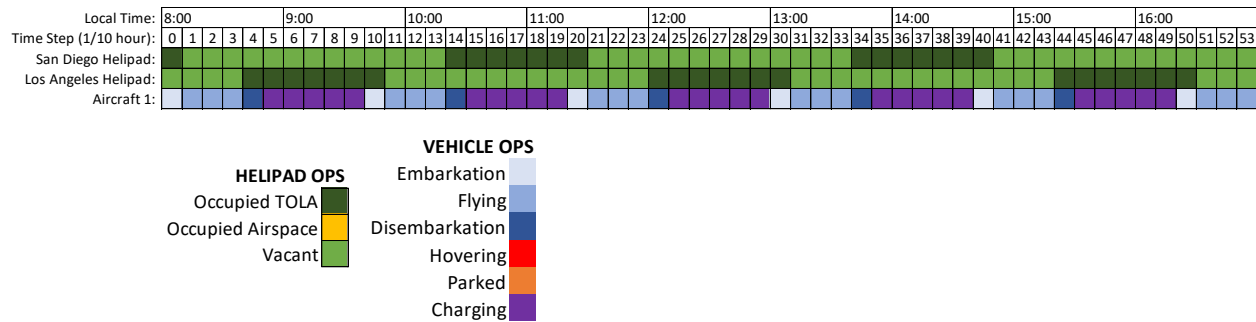


Figure 115. ODM Aviation ConOps diagram for a single aircraft operating the San Diego to Los Angeles with saturated demand.

Table 80 displays the percentage of the day dedicated to various activities involved with the aircraft’s mission in a saturated demand scenario for six one-way trips. As can be seen, vehicle charging accounts for nearly 50% of the aircraft’s operation. Furthermore, if ferrying time to new customer locations or waiting time (after charging) was considered for customers, then the ratio of charge time to revenue flight could become even larger. Additionally, the aircraft is assumed to be fully charged at the beginning of the day and left discharged at the end of the day, so an additional charging cycle must be conducted but was not considered in this analysis.

Table 80. San Diego to Los Angeles ODM aircraft daily operating activity time shares for six one-way trips.

| Operating Activity | Revenue Activity? | Total Time (min) | % of Total Time |
|--------------------|-------------------|------------------|-----------------|
| Embarkation        | Yes               | 30               | 5.4%            |
| Disembarkation     | Yes               | 18               | 3.3%            |
| Flight             | Yes               | 228              | 41.4%           |
| Charging           | No                | 275              | 49.9%           |

Table 80 suggests that for long distance ODM aviation trips, such as between San Diego and Los Angeles, reducing the embarkation or disembarkation time provides little benefit to the overall operation as these activities jointly represent less than 10% of the daily aircraft time share. Rather, focus should be given to selecting shorter flight profiles and reducing the time necessary to re-charge the aircraft.

[Intentionally Left Blank]

## The Beverly Hills Hotel to Los Angeles Airport

### **ConOps Step 1: Customer Submits a Travel Request**

No operational challenge identified for any of the reference missions.

### **ConOps Step 2: Aircraft Routed to the Nearest TOLA**

The Beverly Hills Hotel has no helicopter infrastructure in the immediate vicinity and is an area that produces numerous noise complaints per week, oftentimes due to helicopter tours of the homes in the area and nearby Hollywood Hills communities [30].

The nearest existing TOLA is over 1.1 miles away from the hotel by line of sight, or two miles by roadway. The TOLA is a rooftop EHLF on the Beverly West Residences which is a high-end 22 story condominium complex. The exclusive nature of this building may prevent its use for ODM operations, however there are numerous other helipads in this area. There are also two nearby private heliports roughly a two mile drive from the hotel in Century City. Figure 116 displays the locations of the currently available aircraft ground infrastructure near the Beverly Hills Hotel. The high density of available TOLAs on Wilshire Boulevard and in Century City will limit TOLA congestion and may provide opportunities for extensive aircraft staging.



Figure 116. Current TOLA infrastructure near the Beverly Hills Hotel. © 2016 Google.

### **ConOps Step 3: Customer Takes Ground Transportation from the Origin to the TOLA**

The lack of nearby TOLAs requires customers to take some form of ground transportation to reach the pickup TOLA. If a customer chooses to drive a private vehicle, Century City offers extensive short and long term parking options, however there are limited parking options on Wilshire Boulevard.

#### **ConOps Step 4: Customer Arrives the TOLA and is Prepared for Takeoff**

The primary TOLA selected for this mission is an EHLF on the roof of an apartment building. This facility will likely have the same safety, security and customer access challenges seen in the San Diego reference mission. However, the secondary TOLA option in Century City is a rooftop facility that was previously used as a private heliport. It may therefore already have in place appropriate safety and security measures. Additionally, it is possible that customer access to the TOLA may be simpler. However, entering the private business may still be a potential challenge. Finally, the turn-time for the aircraft remains a potential challenge for both TOLA options.

#### **ConOps Step 5: Flight Segment**

##### *Beverly Hills Hotel to LAX Airspace Considerations*

The relatively short flight from the Beverly Hills Hotel to the Los Angeles International Airport originates within the boundaries of the Santa Monica Class D airspace. The Santa Monica airspace is active between 7:00 AM and 9:00 PM requiring ODM operations to establish 2-way communications with the control tower before takeoff; outside these hours the airspace reverts to Class G.

Beyond the Santa Monica airspace, the flight interacts with the LAX Class B airspace, and potentially the LAX Class D airspace. A Class B shelf overlies the origin point and approach to the airport at 5000 ft MSL limiting flight to a maximum of 200 kts. If approaching LAX below 2700 ft MSL from the north, the ODM flight is also likely to enter the LAX Class D airspace requiring two-way radio communication with ATC. Finally, the airspace immediately surrounding the airport down to the surface level is Class B and requires clearance to enter and land within.

##### *Air Traffic Interaction*

This section reviews potential interactions ODM aircraft may have with other aircraft through the course of the mission.

*Helicopter Operations:* There are three VFR helicopter routes in the proximity of the Beverly Hills Hotel and LAX. LAX helicopter operating rules require transiting, arriving and departing helicopters to fly only within these FAA designated routes. Furthermore, if weather requires Special Visual Flight Rule operations, helicopter operations are required to enter the airport through the Industrial helicopter route to the south of the airport. Non-emergency helicopter flights are also prohibited at night 10:00 PM until 7:00 AM [183]. Finally, a helicopter transition route departing from Santa Monica airport connects with highway 405, and another transition route into Santa Monica passes up from highway 405 from the south before turning west towards the airport as seen in Figure 117 (along with the two proposed flight profiles).

The relatively short length of this reference mission suggests that ODM flights may be operating at low altitudes and are likely to interact with the VFR helicopter routes and airports transitions routes. ODM flights may therefore need to communicate with Santa Monica concerning helicopters entering or exiting along the transition routes, and also communicate with Los Angeles International Airport concerning vehicles traveling the helicopter routes through the Class B airspace.

*Fixed-Wing Aircraft:* The Los Angeles International Airport is one of the highest throughput airports in the world. ODM operations into LAX will interact with a high density of commercial aircraft operations, particularly inside LAX controlled airspace. In addition to these flights, the funneling effects of the Los Angeles Special Flight Rules Area (VFR corridor) may present ODM operations with significant general aviation interaction as well, albeit at higher altitudes than ODM aircraft are likely to operate at for this mission. Finally, both proposed routes pass perpendicular to the Santa Monica standard arrival route within one and a half miles of the runway threshold.

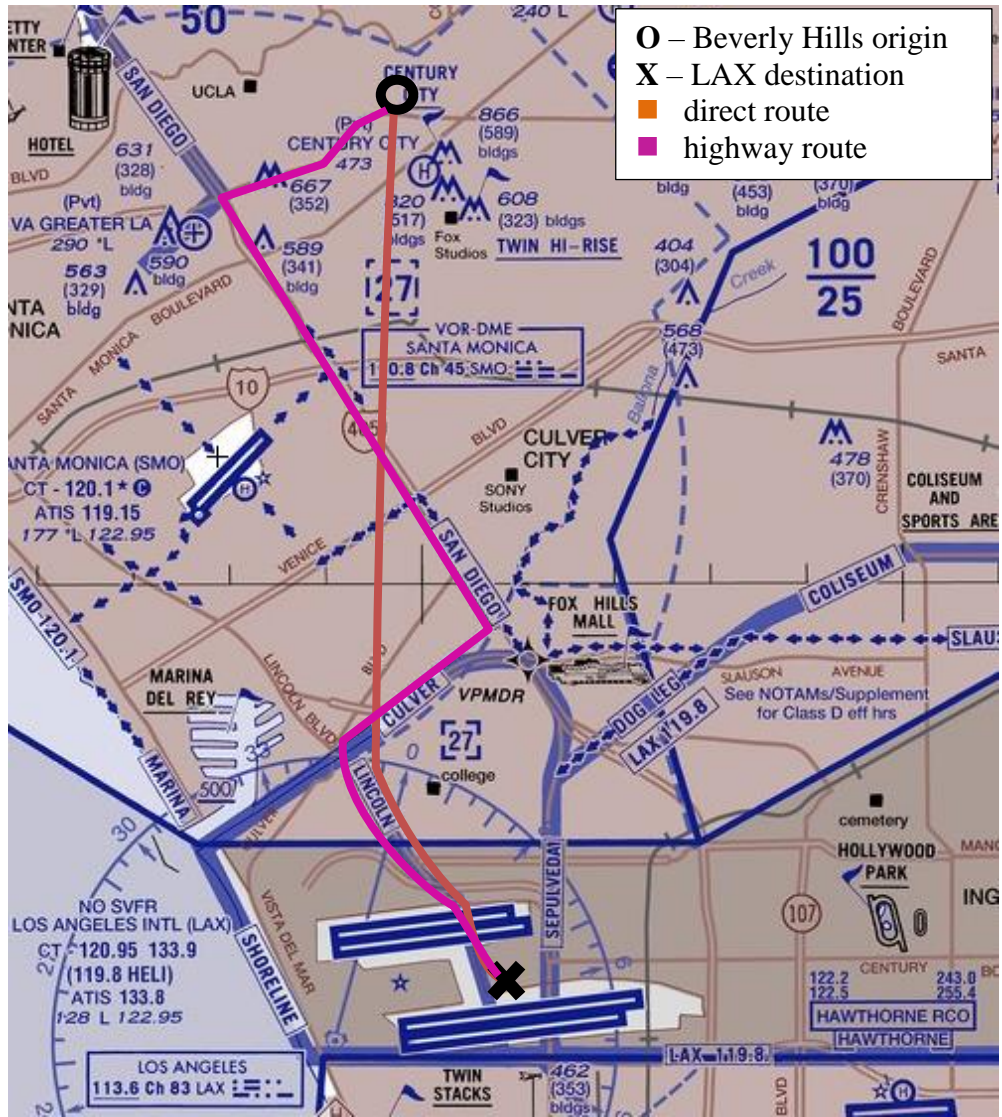


Figure 117. Beverly Hills TOLA on Wilshire Boulevard to LAX heliport route planning on a FAA Los Angeles West Helicopter Route Chart.

### Ground Population Noise Exposure

The area between Beverly Hills and LAX is relatively uniformly densely populated. Current VFR helicopter routes and helicopter transition routes follow major highway arteries in an effort to concentrate aviation noise over regions with higher background exposure. Figure 118 displays a population density map of the reference mission along with the two proposed flight profiles.

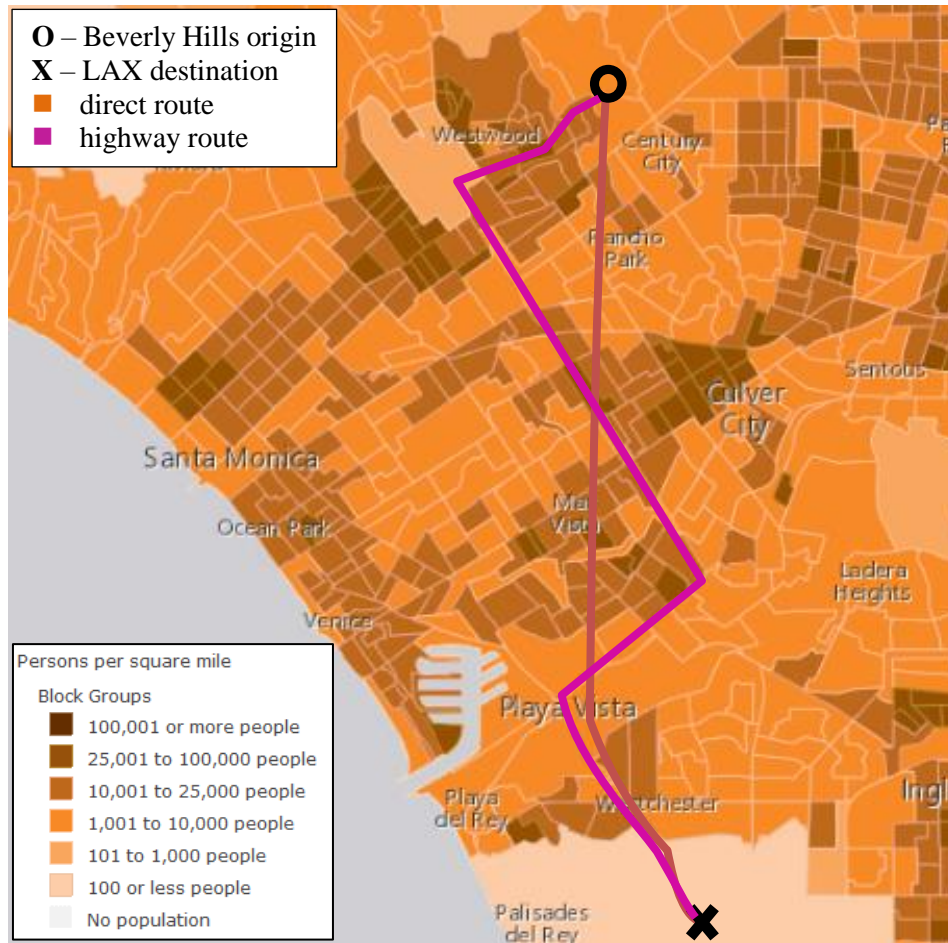


Figure 118. 2012 population density of census block groups between Beverly Hills and the Los Angeles International Airport. *USA\_Population\_Density map* © 2013 Esri, retrieved from [www.arcgis.com](http://www.arcgis.com).

### Mission Flight Profile Development

The first proposed flight profile is a relatively direct route from the origin in Beverly Hills to LAX. The route passes over numerous neighborhoods before connecting with the Lincoln helicopter route to pass midfield over runways 6L and 6R to land at the LAX heliport. The second proposed flight profile flies over highways to approach the airport in an effort to reduce noise perception on the ground. Figure 117 displays both of the potential routes overlaid on the Los Angeles West Helicopter Route Chart.

Due to the simple nature of the routes, a detailed flight profile was not defined for each. The direct route is nine miles in length while the highway following route is 12 miles in length. The resultant flight duration difference between the two routes is on the order of a few minutes. A pilot's choice between these two routes is therefore likely to depend upon air traffic, noise reduction practices, and ATC routing.

### Potential ODM Challenges from the Flight Segment

Perhaps more than any other reference mission presented in this thesis, the Beverly Hills Hotel to LAX mission presents a significant potential ground population noise exposure challenge. The missions require departure from an area of Los Angeles that has been highly outspoken against helicopter operations. The short distance of the trip may result in ODM aircraft flying at relatively low altitudes over densely populated urban regions. Furthermore, the route passes near the Santa Monica community which has been outspoken and active against aircraft noise from operations at the Santa Monica airport. Considering these factors, aircraft noise may be an especially binding constraint for operations in this reference mission.

Low altitude ATC and airspace access, as well as flight vehicle density, may also be pronounced operational challenges for this reference mission. Both the origin and destination locations reside within surface-level controlled airspaces and therefore require ATC approval to enter. The two flight profiles both have extensive interactions with helicopter VFR routes as well as approach and arrival paths into Santa Monica airport: these interactions may increase the flight density challenge. Flight at low altitudes may also increase interaction with UAS, though these vehicles are not commonly authorized to fly within controlled airspaces.

### **ConOps Step 6: Aircraft Arrives at Destination and Customer Disembarks**

Unlike any other TOLA evaluated in the previous reference missions, the airport heliport at LAX provides ODM operations with numerous aircraft parking spots associated with a single TLOF. This facility, although currently not operational, could therefore limit the TOLA congestion and priority concerns. The heliport was also specifically designed to provide easy customer egress to the airport and appropriate safety and security. Numerous parking spots reduce the challenge of aircraft turn-time and the vehicles may be unloaded without tying up the use of the TLOF for other operations. Therefore, only the alternative safe landing location remained a challenge for this step of the reference mission.

### **ConOps Step 7: Customer Takes Ground Transportation to the Final Destination**

In the case of this reference mission, the final destination had an on-site TOLA and no additional "last mile" ground transportation was necessary.

### **ConOps Step 8: Aircraft Recharges Batteries**

Due to the short distance of this reference mission, a single full-electric aircraft could complete up to 14 one-way trips per charge. In a saturated demand situation, this translates to only 18% of operational time being spent charging the aircraft, while 47% was spend in flight. These percentages are dramatically different from the San Diego mission and suggest that current battery charging technologies may not be as severe of a constraint for short distance point-to-point missions.

To better illustrate this finding, Table 81 displays the percent of time required for each phase of the aircraft ConOps for three of the reference missions. These reference missions have dramatically different flight leg distances and reveal the dependency of the number of flights per charge on the required flight length. Furthermore, an interesting trend is seen where the percent of the aircraft operating time dedicated to charging grows profoundly with increasing flight length. This trend among the reference missions reinforces the concept that aircraft charging will be a more binding constraint for missions of longer range.

Table 81. Comparison of charging time requirements as a percentage of the overall mission block time for three reference missions of different flight lengths.

|                    | <b>Redondo Beach</b><br><b>% of Total Time</b> | <b>San Diego</b><br><b>% of Total Time</b> | <b>Beverly Hills</b><br><b>% of Total Time</b> |
|--------------------|--|--|--|
| Embarkation        | 13%  | 5%   | 22%  |
| Disembarkation     | 8%   | 3%   | 13%  |
| Flight             | 52%  | 35%  | 47%  |
| Charging           | 26%  | 56%  | 18%  |
| Flight Length      | 23 mi  | 112 mi                                     | 10 mi  |
| Flights per Charge | 6  | 1  | 14   |



## Appendix C: Review of U.S. Airspace Definitions

This appendix contains a review of current U.S. commercial airspace definitions and discusses the airspaces in the Los Angeles basin.

The Los Angeles basin has one of the most complex and congested airspaces in world. Within Los Angeles County alone there are 27 airports, 138 registered heliports, and hundreds of other Emergency Helicopter Landing Facilities (EHLF). The Los Angeles Airport (LAX) is one of the busiest airports in the world, and its Class B airspace dominates the L.A. Basin. Surrounding the LAX airspace is a complex network of federal airways, VFR routes, helicopter routes, Class C, D, and E airspaces, national defense areas, marine sanctuary and national park flight areas, prohibited airspaces and numerous other airspace demands. Furthermore, air traffic controllers seek to separate helicopters by altitude from higher-performing, faster-moving fixed-wing aircraft [30].

This thesis sought to understand how ODM aircraft and operations may be integrated into the complex existing airspace of southern California in a manner that minimizes operational constraints and protects the integrity and safety of all operations. This section presents an overview of the criteria and constraints for each category or type of airspace present in the case study reference area.

**Class B Airspace:** Two Class B airspaces are contained within the Los Angeles basin case study system boundary. The LAX Class B airspace extends upwards and outwards over the L.A. basin through multiple shelves, or airspace tiers, that contain the airport's approach and departure paths. The LAX airspace has 14 unique segments with different floor and ceiling altitudes spanning from the surface up to a maximum of 10,000 ft MSL.

The San Diego Class B airspace has overlapping and integrated airspace shelves that contain the approach and departure paths for both the San Diego International Airport as well as the Marine Corps Air Station Miramar.

Entrance into Class B airspace requires ATC clearance and a given routing must be followed to provide separation. ODM aircraft under 19,000 pounds are separated by a minimum of 500 feet vertically, through target resolution, or by visual separation. Aircraft must be fitted with a Mode C transponder and two-way radio. Flight beneath the Class B airspace is limited to 200 kts. Flight within the Class B airspace is limited to 250 kts. The 250 kt maximum limit is derived from FAR §91.117(a) and applies to all operations, in any airspace, occurring beneath 10,000 ft MSL. The VFR weather minimums for Class B airspace are 3 statute miles flight visibility, flight clear of clouds and flight with a ceiling of at least 1000 ft AGL.

**Mode C Veil:** A special airspace called the Mode C Veil surrounds the largest airports in the United States. The Mode C Veil sweeps out a 30 nm radius circle from the Los Angeles, San Diego and Miramar airports extending from the surface up to 10,000 ft MSL. Airspaces inside this volume retain all properties of any other airspace designation (Class B, for example), but also require additional aircraft equipage to enter or operate in. All vehicles operating in the Mode C Veil must be equipped with a functioning Mode C transponder. In 2020, all vehicles operating in this veil must also be equipped with ADS-B.

**Class C Airspace:** Five Class C airspaces are contained within the Los Angeles basin case study system boundary. These airspaces typically extend from the surface to 4000 feet AGL within five nautical miles of the primary airport, and then in a shelf from 1200 feet to 4000 feet out to 10 nautical miles of the airport. Entrance into Class C airspace requires the establishment and maintenance of two-way radio communications with ATC prior to entry, however no clearance is required. The aircraft must be fitted with a Mode C transponder and airspeed is limited to 200 kts when within 4 nautical miles of the primary airport in Class C airspace if below 2500 ft AGL; this requirement excludes flight in Class B airspace. The VFR weather minimums area flight visibility of 3 statute miles, operation 1000 feet above, 500 feet below, and 2000 feet laterally of clouds, and flight with a ceiling of at least 1000 ft AGL.

**Class D Airspace:** Thirty Class D airspaces are contained within the Los Angeles basin case study system boundary. Class D airspaces typically extend from the surface up to 2800 feet AGL with a diameter of five statute miles. Entrance to Class D airspace requires the establishment and maintenance of two-way radio communications with the ATC facility prior to entry, however no clearance is required. Aircraft speed is limited to 200 kts when within 4 nautical miles of the primary airport in Class D airspace if below 2500 ft AGL; this requirement excludes flight in Class B airspace. The VFR weather minimums are identical to those for flight in Class C airspace. Please note that there are two special Class D airspaces that are not centered on an airport or control tower, but rather are attached north and south of the LAX Class B airspace.

**Class E Airspace:** A majority of the airspace above 700 ft AGL and below 18,000 ft MSL in the Los Angeles basin that is not designated as Class B, C or D airspace is classified as Class E airspace. While most of the Class E airspaces extend from 700 ft AGL up to 18,000 ft, there are occurrences in Palm Springs and near the Compton/Woodley airport in Los Angeles where Class E extends to the surface. Outside of the more densely populated regions the Class E airspace primarily begins at 1200 ft AGL, rather than 700 ft AGL. Furthermore, dozens of federal airways are present in the L.A. basin that are considered Class E airspace. These airways are each eight nautical miles in width, and reach from 1200 ft AGL up to 18,000 ft MSL. There are no requirements to enter Class E airspace for VFR operations. Below 10,000 ft MSL, the VFR weather minimums are identical to those for flight in Class C airspace.

**Class G Airspace:** All airspace not designated as class A, B, C, D or E is considered to be Class G airspace. Class G airspace extends from the ground up to the overlying Class E airspace at 14,500 feet in the Los Angeles area. There are no entry requirements for flight into Class G airspace, and speeds below 10,000 ft MSL are limited to 250 kts. VFR weather minimums are dependent upon altitude and time of day, however are never more restrictive than the previous classes of airspace. See FAR §91.155 for a full description of the Class G VFR weather minimums. Helicopter and fixed-wing aircraft VFR weather minimums also differ where helicopter requirements are less stringent.

**Special Use Airspaces:** A variety of special use airspaces are defined by the FAA that may place additional equipment or operational requirements upon aircraft and pilots seeking to enter or operate in the airspace. Such airspaces may be permanent, active at only specific times, or active only in specific weather conditions. A brief description of the primary special use airspaces and their associated constraints are provided below, however each airspace is unique and must be considered individual based on the route, time and needs of the ODM mission.

- *Prohibited Areas:* No aircraft may enter or operate in this airspace.
- *Restricted Areas:* Flight in these areas may be restricted and access without authorization during active times may be hazardous.
- *Warning Areas:* Airspace extending from 12 nmi outwards from the coast of the United States containing activity that may be hazardous to nonparticipating aircraft; VFR flights discouraged.
- *Military Operation Areas (MOA):* Active military operations in these airspaces may present hazards to aircraft. VFR operations are discouraged and IFR flights will be routed around or given access through the airspace.
- *Alert Areas:* Airspace with unusual or highly congested activities. Pilots should exercise caution.

Table 82 presents a summary of the primary characteristics and operating constraints of flight in the various airspaces presented. Except for the Mode C Veil, a volume can only be classified as a single airspace type at any given time (however classification may change over time).

Table 82. Los Angeles basin case study airspace type and requirements summary.

| <b>Airspace Type</b> | <b>Composite Altitude Range</b> | <b>Entry Requirements</b>    | <b>Maximum Operating Speed (KIAS)</b>                             | <b>Occurrences in LA Basin</b> |
|----------------------|---------------------------------|------------------------------|---|--------------------------------|
| Class B              | SFC–10,000 ft MSL               | ATC clearance                | 250   | 2                              |
| Underlying Class B   | SFC–9000 ft MSL                 | None                         | 200   | 2                              |
| Class C              | SFC–4000 ft AGL                 | Two-way radio communications | 200 within 4 nmi of airport when below 2500 ft AGL; 250 otherwise | 5                              |
| Class D              | SFC–2500 ft AGL                 | Two-way radio communications | 200 within 4 nmi of airport when below 2500 ft AGL; 250 otherwise | 28                             |
| Class E              | SFC–18,000 ft MSL               | None for VFR                 | 250 under 10,000 ft MSL   | 5                              |
| Class G              | SFC–18,000 ft MSL               | None                         | 250 under 10,000 ft MSL   | N/A                            |
| Mode C Veil          | SFC–10,000 ft MSL               | Mode-C transp. ADS-B (2020)  | N/A   | 3                              |
| Prohibited           | Variable                        | Prohibited                   | N/A   |                                |
| Restricted           | Variable                        | Variable                     | 250 under 10,000 ft MSL   | 9                              |
| Warning              | Variable                        | None                         | 250 under 10,000 ft MSL   | Numerous                       |
| MOA                  | Variable                        | None                         | 250 under 10,000 ft MSL   | 5                              |

## Appendix D: Overview of ODM Aviation Externalities and Impacts

Table 83 presents a selection of environmental justice externalities identified in this thesis. A concise description of how each externality may result from the implementation of ODM Aviation services is presented. Furthermore, potential feedback influences on the ODM Aviation networks themselves are hypothesized. The table has been color coded to indicate beneficial externalities (green), negative externalities (red), and impacts with uncertain or mixed externalities (grey). Table 84 reviews a selection of the social equity externalities in the same format.

Table 83. Potential environmental justice externalities resulting from ODM Aviation.

| ODM Aviation Externality   | Externality Description and Potential Influence on ODM Aviation   |
|--|---|
| Co-location of environmental costs and benefits  | <p><u>Description:</u> Unlike airports and highways, TOLAs are likely to be co-located with the communities that utilize them and do not cut through other communities (with surface infrastructure).</p> <p><u>Influence:</u> Many of the costs of ODM Aviation (such as noise, emissions, and vibrations) are internalized by the communities that choose to use the service; this may reduce public activism against ODM operations.</p>   |
| Increased environmental burden due to accelerated urban sprawl                         | <p><u>Description:</u> ODM Aviation may increase the rate that individuals move to suburbs or exurbs on the metropolitan periphery. These communities have a significantly higher household carbon footprint than urban developments. Therefore the overall environmental burden of a city could increase as a result of ODM Aviation.</p> <p><u>Influence:</u> Governments may impose carbon taxes or other schemes on ODM operations.</p>   |
| Reduced lifecycle environmental impacts compared to existing aircraft charter services | <p><u>Description:</u> ODM operations with distributed electric propulsion aircraft reduce the lifecycle environmental impacts of flight compared to helicopters or conventionally powered aircraft.</p> <p><u>Influence:</u> ODM aircraft may be viewed as a more sustainable form of short-range air transportation than current vehicles.</p>  |
| Increased sustainability of a city's transportation portfolio                          | <p><u>Description:</u> ODM aircraft produce more GHG emissions per passenger mile than new automobiles when comparing performance on identical routes in ideal operating conditions. However, ODM aircraft displayed the potential to significantly reduce GHG emissions compared to cars if operated at high load factors, on routes that avoid surface congestion or geographic barriers, and in a well-balanced demand network. If ODM Aviation services are used for routes that meet these conditions they may reduce the GHG emissions of the overall transportation system by replacing high-emitting surface missions.</p> <p><u>Influence:</u> ODM Aviation may leverage private or public funding to develop infrastructure and operate services along routes that provide emissions reduction opportunities.</p> |

Table 84. Potential social equity externalities resulting from ODM Aviation.

| ODM Aviation Externality   | Externality Description and Potential Influence on ODM Aviation   |
|--|---|
| Increased access to mobility for currently underserved areas     | <p><u>Description:</u> Nodal TOLA infrastructure may be developed in <i>transit deserts</i> at relatively low cost and low land usage compared to surface-based, linear transportation infrastructure.</p> <p><u>Influence:</u> ODM Aviation may leverage public or private funding to develop infrastructure and service in these communities.</p>   |
| Reduced housing costs in the urban core                          | <p><u>Description:</u> Urban air mobility may enable high-income individuals who previously lived in the urban core to commute to suburban homes. This could either enable lower-income individuals to afford to live in the urban core, or could lead to a hollowing out and decay of the city center.</p> <p><u>Influence:</u> If city governments anticipate or experience reduced tax revenue, they may place operational limits or additional taxes on ODM Aviation operations.</p>  |
| Intensified socio-economic segregation                           | <p><u>Description:</u> High-income individuals may utilize ODM Aviation to move to fly-in communities geographically and socially isolated from underprivileged communities.</p> <p><u>Influence:</u> If city governments anticipate or experience reduced tax revenues, they may place operational limits or additional taxes on ODM Aviation operations to such communities.</p>  |
| Regional urbanization  | <p><u>Description:</u> ODM Aviation may provide high speed transit between city centers in a polycentric metropolitan region at a fraction of the development cost of surface transportation modes. Polycentric city structures are proposed to be more equitable and reduce environmental impacts.</p> <p><u>Influence:</u> ODM Aviation may leverage public or private funding to develop infrastructure and service these high-demand routes between city centers.</p>   |
| Displaced ridership and funding for surface transportation modes | <p><u>Description:</u> ODM Aviation may re-mode high-income individuals away from public transit options or automobile travel on toll roads.</p> <p><u>Influence:</u> Taxes may be levied on ODM operations to recoup lost transportation revenues.</p>   |
| Altered market for careers in transportation services            | <p><u>Description:</u> ODM Aviation may provide numerous new low and high skill jobs in the near-term while minimally impacting other transportation jobs. However, increased automation and network scale in the far-term may reduce the number of piloting, driving, sales, maintenance and manufacturing jobs related to transportation.</p> <p><u>Influence:</u> ODM Aviation may be viewed as an economic stimulus in the near-term, but may experience opposition from labor and the public as increasing levels of automation are adopted.</p> |

