

Utah State University

DigitalCommons@USU

All Graduate Theses and Dissertations

Graduate Studies

5-2012

Traffic Operations Analysis of Merging Strategies for Vehicles in an Automated Electric Transportation System

Derek Rulon Freckleton
Utah State University

Follow this and additional works at: <https://digitalcommons.usu.edu/etd>



Part of the [Civil Engineering Commons](#)

Recommended Citation

Freckleton, Derek Rulon, "Traffic Operations Analysis of Merging Strategies for Vehicles in an Automated Electric Transportation System" (2012). *All Graduate Theses and Dissertations*. 1418.

<https://digitalcommons.usu.edu/etd/1418>

This Thesis is brought to you for free and open access by the Graduate Studies at DigitalCommons@USU. It has been accepted for inclusion in All Graduate Theses and Dissertations by an authorized administrator of DigitalCommons@USU. For more information, please contact digitalcommons@usu.edu.



TRAFFIC OPERATIONS ANALYSIS OF MERGING STRATEGIES
FOR VEHICLES IN AN AUTOMATED ELECTRIC
TRANSPORTATION SYSTEM

by

Derek Rulon Freckleton

A thesis submitted in partial fulfillment
of the requirements for the degree

of

MASTER OF SCIENCE

in

Civil and Environmental Engineering

Approved:

Kevin Heaslip
Major Professor

Anthony Chen
Committee Member

Joseph Caliendo
Committee Member

Mark McLellan
Vice President for Research and Dean of the
School of Graduate Studies

UTAH STATE UNIVERSITY
Logan, Utah

2012

Copyright © Derek R. Freckleton 2012
All Rights Reserved

ABSTRACT

Traffic Operations Analysis of Merging Strategies
for Vehicles in an Automated Electric
Transportation System

by

Derek Rulon Freckleton, Master of Science

Utah State University, 2012

Major Professor: Dr. Kevin P. Heaslip
Department: Civil & Environmental Engineering

Automated Electric Transportation (AET) is a concept of an emerging cooperative transportation system that combines recent advances in vehicle automation and electric power transfer. It is a network of vehicles that control themselves as they traverse from an origin to a destination while being electrically powered in motion – all without the use of connected wires.

AET's realization may provide unparalleled returns in the form of dramatic reductions in traffic-related air pollution, our nation's dependence on foreign oil, traffic congestion, and roadway inefficiency. More importantly, it may also significantly improve transportation safety by dramatically reducing the number of transportation-related deaths and injuries each year as it directly addresses major current issues such as human error and adverse environmental conditions related to vehicle emissions. In this thesis, a logical strategy in transitioning from today's current transportation system to a future automated and electric transportation system is identified.

However, the chief purpose of this research is to evaluate the operational parameters where AET will be feasible from a transportation operations perspective. This evaluation was accomplished by performing lane capacity analyses for the mainline, as well as focusing on the

merging logic employed at freeway interchange locations. In the past, merging operations have been known to degrade traffic flow due to the interruptions that merging vehicles introduce to the system. However, by analyzing gaps in the mainline traffic flow and coordinating vehicle movements through the use of the logic described in this thesis, mainline traffic operations can remain uninterrupted while still allowing acceptable volumes of merging vehicles to enter the freeway. A “release-to-gap” merging algorithm was developed and utilized in order to maximize the automated flow of traffic at or directly downstream of a freeway merge point by maximizing ramp flows without causing delay to mainline vehicles. Through these tasks, it is the hope of this research to aid in identifying the requirements and impending impacts of the implementation of this potentially life-altering technology.

(94 pages)

PUBLIC ABSTRACT

Traffic Operations Analysis of Merging Strategies
for Vehicles in an Automated Electric
Transportation System

by

Derek Rulon Freckleton

Automated electric transportation has the potential to revolutionize the way people move by providing unparalleled benefits to human health and safety, economic independence, and quality of life. It is a system where vehicles with no emissions control themselves as they cooperatively move people from point “A” to point “B.” Vehicle automation aims to eliminate human error from the task of driving, making the roads safer and leaving drivers able to perform other tasks as they desire while they travel. Also, through wireless in-motion electric power transfer, the gas tank may finally be completely excluded from vehicles without sacrificing freedoms in range or mobility. This feat will aid in the elimination of traffic-related air pollution as well as our nation’s dependence on foreign oil. Other benefits affecting quality of life may also include reduced traffic congestion and roadway inefficiency.

However, despite the many benefits anticipated by this new system of transportation, a framework upon which it can be built is yet to be developed. This research provides a portion of that framework by specifying a logical transition strategy for moving from today’s transportation system to this future automated and electric transportation system. Yet its chief purpose is to evaluate the operational parameters where AET will be feasible from a transportation operations point of view. This evaluation is accomplished by performing lane capacity analyses of the freeway, as well as focusing on the merging maneuvers at freeway interchange locations.

Through the use of the logic presented in this thesis, freeway traffic operations can remain unaffected by vehicles entering freeway traffic flow, allowing automated freeway lanes the ability to quadruple their capacity. It is the hope of this research to aid in identifying the requirements and quantifying the potential impacts of an automated electric transportation system.

ACKNOWLEDGMENTS

I would like to thank Dr. Kevin Heaslip for bringing me onto the Automated Electric Transportation research project. It has been a challenging and enjoyable experience that would not have been possible without his guidance and his confidence in my abilities. I would also like to thank my committee members, Dr. Joe Caliendo and Dr. Anthony Chen, for their support and assistance throughout my education at Utah State University.

I give special thanks to my wife, Jamie, for her love and encouragement in my academic and professional development. Finally, I thank my family, friends, and colleagues for their patience and support as I worked my way from a conceptual idea to this final document. I could not have done it without all of you.

Derek R. Freckleton

CONTENTS

	Page
ABSTRACT	iii
PUBLIC ABSTRACT	v
ACKNOWLEDGMENTS	vii
LIST OF TABLES	x
LIST OF FIGURES	xi
CHAPTER	
1. INTRODUCTION	1
Research Question	4
General Approach	4
Major Research Theories	6
Anticipated Contributions	6
2. LITERATURE REVIEW	8
Wireless Power Transfer for Vehicle Electrification	8
Human Factors in Transportation	10
Car Following Theory and Car Following Models	14
Car Following Theories	14
Car Following Model Development	16
Microscopic/Macroscopic Models	17
Gipps' Car Following Model	18
Vehicle Automation	20
3. TRANSITION STRATEGY AND MODEL DEVELOPMENT	26
Stationary Charging	27
Personal Application	27
Public Applications	28
Semi-Stationary Charging	29
Private Applications	29
Public Transportation Applications	30
Dynamic Charging (Charge-In-Motion)	31

eLanes	31
Dedicated AET Lanes.....	32
AET Nomenclature	33
Model Development.....	36
Check-In	37
Check-Out.....	38
Configuration Design	38
4. RESEARCH METHODOLOGY	41
Research Questions and Hypotheses.....	41
Hypotheses Related to AET Interchange Impacts.....	41
Assumptions	42
Equations for Maximum Capacity Analysis	45
Gap Formation for Check-In	46
Entrance Algorithm & Analysis Equations	49
Performance Measures	55
5. ANALYTICAL RESULTS	56
Optimal Mainline Capacity	56
Ramp Capacity	58
Effective Mainline Capacity	61
6. SUMMARY AND CONCLUSION.....	68
Conclusion.....	69
Recommendations for Future Research	70
REFERENCES	72
APPENDIX.....	79

LIST OF TABLES

Table	Page
1. Driver Error and Incident Causation Factors.....	12
2. Optimal Mainline Capacity, [vph].....	62
3. Effective Capacity (AHS), [vph].....	63
4. Effective Capacity (AET), [vph].	64

LIST OF FIGURES

Figure	Page
1. Conceptual Schematic of Automated Electric Transportation	2
2. Fatalities and Fatality Rate per 100M VMT by Year	10
3. Crash Incident Causation Factors	13
4. Human Reaction Time vs. Automated Delay	17
5. Basic Assumption of Car Following Theory	18
6. 85th-Percentile Reaction Times	23
7. Charge-In-Motion Illustration.....	32
8. AET Interchange Schematic	39
9. AET Entrance Algorithm Flowchart.....	49
10. Maximum Mainline Capacity Flow vs. Density	57
11. Simulated Results for Maximum Mainline Capacity	58
12. Ramp Capacity vs. Mainline Flow	59
13. Capacity Comparison.....	65

CHAPTER 1

INTRODUCTION

The transportation system of the United States has had significant impacts on the nation's development, both geographically and economically. However, tens of thousands of lives are lost each year due to externalities of today's transportation system. The majority of these lives are lost as a result of some form of human error, while much of the remainder are the result of adverse environmental conditions, such as degraded air quality. Addressing these issues has led to increased interest in cooperative transportation systems.

A cooperative transportation system is defined as a system in which drivers, vehicles, and the roadway itself all function as a single, integrated system designed to save lives, reduce injuries, and enhance quality of life, while maintaining or increasing travelers' productivity and mobility (*1*). These transportation systems have become a topic of increased interest due to recent enabling technological advances.

Intelligent communication between vehicle and infrastructure has been investigated in hopes of increasing safety and efficiency. Vehicle manufacturers have implemented various technologies within vehicles to aid drivers in avoiding hazardous situations. In addition, the automobile industry has continually sought to improve the environmental impact of vehicles by reducing vehicles' carbon emissions, as has been seen through the research of biofuel technology, plug-in electric vehicles (PHEVs), and fuel cell technology. However, a solution which addresses these issues holistically could provide significant breakthroughs in transportation intelligence, enhancing quality of life.

Automated Electric Transportation (AET) has the potential to be a revolutionary cooperative transportation system that combines recent advances in vehicle automation and wireless electric power transfer. The AET concept is a network of vehicles that can be

autonomously or cooperatively controlled while being wirelessly powered in motion. Automated control of vehicles can be achieved through wireless communication from vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I/I2V), and infrastructure-to-infrastructure (I2I). Electrically powering vehicles in motion, even at speeds equal to or greater than current freeway travel, can be achieved through a wireless power transfer between the vehicles and charging pads embedded in the roadway infrastructure. Figure 1 provides a graphical representation of the underlying concepts involved in AET.

AET's realization may provide unparalleled returns in the form of dramatic reductions in traffic-related air pollution, our nation's dependence on foreign oil, traffic congestion and roadway inefficiency. More importantly, it may also significantly improve transportation safety by dramatically reducing the number of transportation-related deaths and injuries each year as it directly addresses issues such as human error and adverse environmental conditions.

The purpose of this research is to evaluate the operational parameters where AET will be feasible. As a new form of transportation that cannot be built instantaneously, it is certain that a

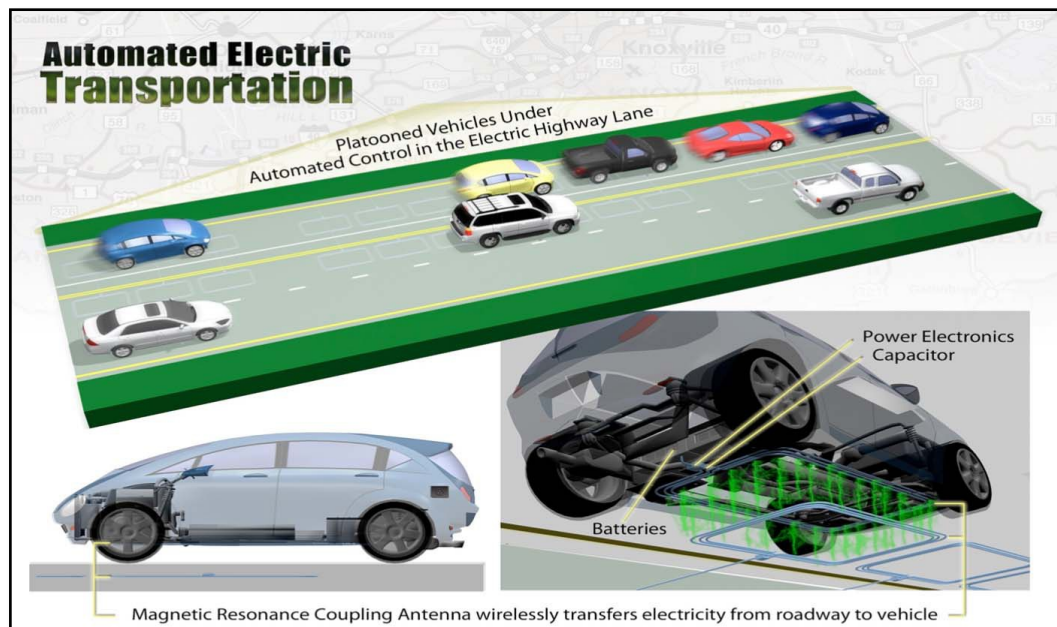


FIGURE 1. Conceptual Schematic of Automated Electric Transportation (2).

phased implementation of AET systems will be required. For this reason, a logical strategy for transitioning from today's current transportation system to a future automated and electric transportation system is necessary, as that point has been overlooked in previous highway automation efforts (3).

As the transition to AET occurs, a control transfer process is required in which vehicles toggle from manual control (human-driven) to automated control (machine-driven), and vice-versa. This process of transferring vehicle control should be included in the check-in and check-out procedures for AET travel. Also for these procedures, an analysis of merging and diverging vehicles into and out of traffic flow at designated AET freeway interchanges must be performed.

Specifically, this research focuses on the analysis of the merging operations. It will be conducted through the use of analytical theory and mathematical equations, and verified through the use of traffic micro-simulation software. The evaluation of the AET system at a single freeway interchange location will be accomplished by performing a lane capacity analysis for the mainline, as well as focusing on the merging logic employed at these locations. In the past, merging operations for a single lane have been known to degrade traffic flow due to the interruptions that merging vehicles introduce to the system (4, 5). However, by analyzing gaps in the mainline traffic flow and coordinating vehicle movements, mainline traffic operations can remain uninterrupted while still allowing acceptable volumes of merging vehicles to enter the freeway. A "release-to-gap" merging algorithm is utilized in order to maximize the automated flow of traffic at or directly downstream of a freeway merge point by maximizing ramp flows without causing delay to mainline vehicles.

The significance of the results obtained is that they provide quantified measurements in automated lane capacities and traffic flows. Under the logic outlined in this thesis, automated lane capacities may be more than quadrupled compared to freeway lanes today. These values also incorporate the ability to maximize ramp operations without imposing delay on mainline

traffic flow. Therefore, even at merging areas of the freeway, actual automated traffic flows approach theoretical values for maximum capacity. However, while it does not actually reach maximum capacity, it is significant that any capacity loss experienced is the result of unused headway space, rather than the result of some delay. This information may be useful in applications of cost/benefit analyses for land use and the acquisition of right-of-way.

Research Question

The major question on which this research focuses is: “In transitioning to an automated electric transportation system, what impacts will an automated vehicle interchange have on highway traffic operations?” Addressing this question effectively calls for the ability to assess traffic situations under local conditions at a microscopic simulation level. Such simulation tools improve the capability to visualize the impact of the application of these emerging technologies in the transportation arena as they are applied in a virtual transportation network. These tools also aid in quantitatively assessing the requirements for the successful implementation of AET. The information gathered could be useful to individuals designing similar systems at various locations.

General Approach

There have been difficulties in assessing the feasibility, as well as the impacts and requirements of such transportation technologies, as this system is currently theoretical and established analysis methodologies do not currently exist. Even micro-simulation tools are not currently capable of addressing the dynamics of such a transportation system because traditional car following and lane changing algorithms are based on normal or near-normal traffic flow conditions. With the implementation of the technology provided in AET, those traffic conditions will be altered. Certain parameters (e.g. speed, flow, and capacity) may be increased, while

others (i.e. headway spacings and reaction times) may be decreased. The dynamics surrounding how a vehicle moves will be different for an automated electric vehicle.

The inability for the simulation tools to model an AET system is challenging because successful implementation requires such a system to be modeled, simulated, and analyzed. Transportation professionals need models that are sensitive to V2V interaction as well as V2I/I2V interaction simultaneously. They are also in need of models that adequately define and simulate the movement of AET-type vehicles. Therefore, this research will be coupled with research performed by others to build such a model for the analysis of the check-in procedure for an AET highway interchange.

Therefore, the analysis methodology that was used in this research incorporates the development of an automated entrance algorithm within a micro-simulation software package. Within the software, modifications to traditional car following and lane changing behavior were made to allow vehicles to travel within tightly spaced platooning structures. Then, considering this structure, the algorithm functions similarly to an advanced gap-based ramp metering system such that queued vehicles on the ramps must await acceptable gaps in the mainline to be allowed to merge into automated traffic flow. This “release-to-gap” merging logic thus accomplishes the merging maneuver for automated vehicles without imposing any significant interruption to the mainline flow, as was proven by Ran et al. (6), and maintains the platooning structure with the specified parameters for maximum platoon size and spacing.

Ran’s study also explains that the consequence of prioritizing the mainline flow over the ramp flow in this way is that the mainline will be able to operate with minimal impact from the merging maneuver, which was the goal of this project. Thus, the algorithm developed inherently gives priority to mainline flows, which in turn transfers any delay that would be experienced on the mainline from a merging maneuver to queued vehicles on the ramp. However, while delay may be transferred to the ramp, it should be noted that large ramp queues typically only develop

under conditions of high mainline flows and few available gaps for merging. It stands to reason that under these conditions, mainline flows should take priority over ramp flows in order to move larger volumes of traffic.

Major Research Theories

The major theory that will drive the research is that the manner by which a vehicle moves transforms as it switches between manual operation to automated operation. Implicit in this theory is that traditional car following behavior must be modified to incorporate smaller headway spacings, smaller gap acceptances, and altered lane-changing or merging/diverging behavior. It is anticipated that those changes will have measurable impacts on traffic flow at locations where interruptions occur (e.g. freeway interchanges).

Another major theory that will drive the research is that as wireless energy transfer technology develops, it may eventually penetrate into mainstream automobile design. The ability to expand the traveling range of electric vehicles will likely push the development of on-demand charge-in-motion technology, and vehicle automation may provide benefits in maximizing energy transfer efficiency. Thus, the concepts of automating and electrifying vehicles go hand-in-hand for a future improved and sustainable transportation system.

Anticipated Contributions

It is anticipated that with AET's implementation, many dramatic and considerable benefits in various areas are possible. These areas include human health and safety, economic independence, and quality of life. This research will provide a foundation upon which this technology may be further developed by outlining a logical transition strategy and quantifying the requirements and traffic operations impacts of the merging strategy developed for AET freeway

interchanges. Future researchers will then be provided with a means to further quantify the specific benefits mentioned previously.

CHAPTER 2

LITERATURE REVIEW

The topics that this literature review examines are: wireless power transfer for vehicle electrification, human factors in transportation, car following theory and car following models, and vehicle automation efforts. The purposes for evaluating each of these topics are detailed below:

- Wireless power transfer for vehicle electrification was reviewed to help determine the potential impact of this technology on the future of surface transportation. A portion of this impact will be in the performance measures for an individual vehicle. Another portion will be the potential impact electric vehicles may have on environmental conditions relating to human health.
- Transportation literature related to human factors was analyzed to understand the impacts of automated driving on transportation safety and traffic flow. Human error and driver behavior, including reaction time, are key factors in those facets of transportation.
- Car following theory and car following models were examined in order to expand on the current knowledge base in automated vehicle traffic flows.
- Previous vehicle automation efforts will be studied to show that automated vehicles introduce distinct differences in vehicle movement with respect to traditional car following theory.

Wireless Power Transfer for Vehicle Electrification

Currently, the burning of petroleum is by far the most common energy source for surface transportation vehicles. As a result, according to the U.S. Environmental Protection Agency (EPA) (7), the automobile is the single greatest source of pollution in numerous cities across

America. A study completed in 2000 estimated the health effects of traffic-related air pollution in Austria, France and Switzerland. That report concluded that approximately 22,000 deaths (out of a total 40,000 estimated deaths related to air pollution) were due specifically to traffic-related air pollution (8).

Consequently, technologies have emerged that are transforming vehicular travel, including the utilization of electricity to power a vehicle. In particular, two types of technologies currently exist that provide highly efficient, wireless energy transfer: magnetic resonance coupling antennas and inductive coupling using a coaxial-winding transformer (9, 10). Preliminary physical tests for stationary charging using these technologies have shown 90% efficient power transfers of 5 kilowatts over a 10-inch gap simulating the distance between the road surface and the bottom of a vehicle (11). Other tests using mathematical simulations have shown the ability to transfer 10 kilowatts of electrical energy over distances of 6.5-feet at efficiencies as high as 97% (12).

However, one disadvantage of electric vehicles is that electricity is difficult and expensive to store. Most electric vehicles today can only travel approximately 100-200 miles on a single charge (13). Without the option of re-charging when that energy has been expended, drivers are limited to a range of about 50-100 miles for round trip travel; and “quick charges” to 80% capacity require 30 minutes while fully re-charging a battery can take anywhere from 4 to 8 hours (13). As a result, the adoption of these vehicles by the public has been slow.

AET resolves this issue by offering the ability to deliver electric energy on demand, in real time, to moving vehicles using “charge-in-motion” technology. In an AET system, wireless charging pads would be installed within the transportation infrastructure. By reducing the spacing between charging pads, vehicles would begin to have the capability of being powered and even re-charged while in motion, even at freeway speeds or greater. This is known as “charge-in-motion” technology.

Human Factors in Transportation

According to the Centers for Disease Control and Prevention (CDC) (14), motor vehicle-related injuries are the leading cause of death in the United States for individuals between the ages of 5 and 34. In 2009, the National Highway Traffic Safety Administration (NHTSA) reported an estimated 2.217 million people being injured in motor vehicle crashes (15). In addition, the U.S. Department of Transportation (USDOT) (15) announced that the total number of highway fatalities in 2009 totaled 33,808.

In light of those statistics, many efforts have been made to improve the safety of our roadways, and it has improved over the years (16). In fact, over the last 60 years, the fatality rate per 100 million vehicle miles traveled (VMT) has consistently decreased, as shown in Figure 2. Although the number of fatalities per year has remained relatively constant over the years, the actual ratio of fatalities due to motor vehicle-related injuries per capita has decreased by over 50% (17, 18).

While a portion of the credit may be attributed to advances in medical technology, for example, another significant portion is likely due to advances in transportation technology. Road safety audits have resulted in vast improvements in crash prevention, barriers separating traffic flows have been installed, speed limits and geometric designs have been adjusted, and sight triangles and sight distances have been analyzed. Also, despite these efforts, accepting that motor

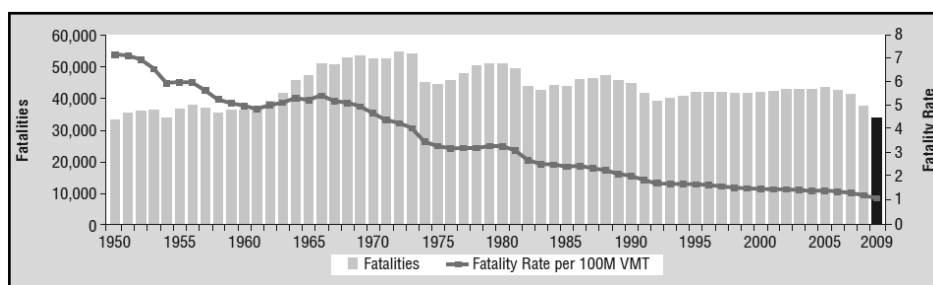


FIGURE 2. Fatalities and Fatality Rate per 100M VMT by Year (19).

themselves to protect their passengers. Examples of these improvements include seatbelts, airbags, anti-lock brakes, crumple zones, traction control, advanced cruise control, and collision avoidance technology.

One of the main safety benefits to automating vehicle travel lies in the results expected by taking the human factors out of driving. A common phrase used for the justification of some error or mistake is, “it’s only human.” Although no universally accepted definition of human error technically exists, the working definitions of errors and mistakes developed by Reason (20) give adequate insight. Error was defined as “a generic term to encompass all those occasions in which a planned sequence of mental or physical activities fails to achieve its intended outcome, and when these failures cannot be attributed to the intervention of some chance agency.” Mistakes were defined as “deficiencies or failures in the judgmental and/or inferential processes involved in the selection of an objective or in the specification of the means to achieve it, irrespective of whether or not the actions directed by this decision-scheme run according to plan.”

Many studies have been completed in order to identify common driver errors and error-causing conditions in motor vehicle crashes. Using data collected from documented incident cases, on-site accident investigations, and accident evaluations, four categories of incident causation factors were developed: human conditions and states, human direct causes, environmental factors, and vehicular factors. A summary of common driver errors and incident causation factors is shown in Table 1 (21).

Upon inspection of Table 1, one can see that human factors (the two left columns) account for the majority of incident causation. In fact, according to the study that produced the results of the table, it was found that overall, driver error played a part in 93% of the road crashes analyzed, as shown in Figure 3 (21).

Understanding, controlling, and eliminating driver deficiencies is vitally important to

TABLE 1. Driver Error and Incident Causation Factors.

Human Conditions and States	Human Direct Causes	Environmental Factors	Vehicular Factors
<ul style="list-style-type: none"> • Alcohol impairment • Other drug impairment • Reduced vision • Critical non-performance • Emotionally upset • Pressure or strain • In hurry • Driver experience • Vehicle unfamiliarity • Road over-familiarity • Road/area unfamiliarity 	<ul style="list-style-type: none"> • Failure to observe • Inattention • Internal distraction • External distraction • Improper lookout • Delay in recognition • Misjudgment • False assumption • Improper maneuver • Improper driving technique or practice • Inadequately defensive driving technique • Excessive speed • Tailgating • Excessive acceleration • Pedestrian ran into traffic • Panic or freezing • Inadequate directional control 	<ul style="list-style-type: none"> • Control hindrance • Inadequate signs and signals • View obstruction • Design problems • Maintenance problems • Slick roads • Special/transient hazards • Ambient vision limitations • Rapid weather change 	<ul style="list-style-type: none"> • Tire and wheel problems • Brake problems • Engine system failures • Vision obscured • Vehicle lighting problems • Total steering failure

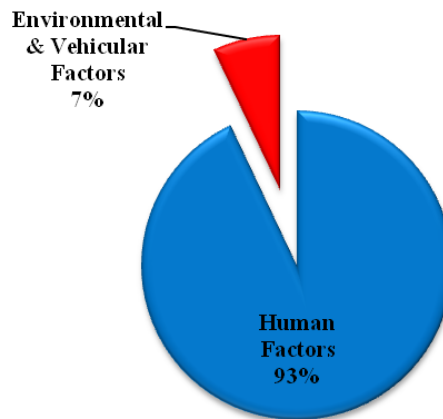


FIGURE 3. Crash Incident Causation Factors.

mitigating risk and ensuring safe transportation on our roadways. Automating the task of driving directly addresses this very significant crash-causing factor in human error. AET therefore has the potential to significantly reduce the annual number of deaths, injuries, and motor vehicle crashes.

Human factors are also important in the modeling of driver behavior in car following and merging scenarios. Driver awareness, reaction time, and gap acceptance are key factors in determining changes in traffic flow, as discussed by Koppa (22). In merging from an acceleration lane onto a freeway, the data for a four-lane facility at roughly 55 mph with a one-second allowance for the ramp necessitates a gap of about 4.5 seconds. Theoretically as short a gap as three car lengths can be accepted if vehicles are traveling at about the same speed, as they would be in merging from one lane to another. Koppa also states that this is the minimum, however, and at least twice that gap length should be used as a nominal value for such lane merging maneuvers.

By utilizing the concepts of V2V, V2I, and I2I communication, automated vehicles may be able to significantly reduce that acceptable gap by eliminating human error, increasing vehicle awareness, and decreasing perception and reaction times. This theory simultaneously resolves other transportation issues, such as capacity and roadway efficiency. Capacity will be increased,

without the need for additional right-of-way, and congestion will decrease due to less severe interruptions in traffic flow.

Car Following Theory and Car Following Models

Car following models shape the link between individual vehicle behavior (microscopic) and streams of vehicles and their corresponding flow and stability properties (macroscopic) (23). In order to modify the car following models present in current simulation packages, an understanding of traditional car following models is required.

Car Following Theories

Car following is a task that has been of interest since the development of the automobile, and for over half a century, theories describing how one vehicle follows another have been widely studied (24, 25, 26, 27). However, with roadway capacity and roadway efficiency continuing to decline, this topic has become a subject of increased importance in transportation/traffic engineering and safety research (27). Car following theories consider the inter-vehicle spacing between vehicles as well as the speed of individual vehicles. They are mathematical models that express a vehicle's acceleration as a function of the speed differential between the leading and following vehicles. As automated systems seek to replicate human driving behavior through control of the accelerator, establishing a car following model for automated vehicles is now a topic of increased interest and importance.

Average inter-vehicle spacing is an important car following characteristic that one vehicle following another would maintain. This is due to the fact that capacity estimations of a single lane roadway are based on the speed-spacing relationship shown in the following equation, modified from Rothery's capacity equation (23):

(2.1)

$$C = 5280 * \frac{u}{(l + h)}$$

where

C = capacity of a single lane, [vehicles per hour, vph]

u = speed, [miles per hour, mph]

l = average effective vehicle length, [feet, ft]

h = average space headway distance from the front bumper of following vehicle to the rear bumper of leading vehicle, [ft]

Through observational studies, an operative speed-spacing relationship to estimate the capacity of single lanes was established in the first Highway Capacity Manual (28). The relationship obtained from these studies is represented by the following modified equation:

(2.2)

$$h = \left(\frac{5280}{3600} * \alpha u \right) + \left(\beta \left[\frac{5280}{3600} * u \right]^2 \right)$$

where

h = average space headway distance from the front bumper of following vehicle to the rear bumper of leading vehicle, [ft]

α = reaction time, [seconds, s]

u = speed, [mph]

β = reciprocal of twice the maximum average deceleration of a following vehicle, [s^2/ft]

The second term in Equation 2.2, $\beta \left[\frac{5280}{3600} * u \right]^2$, is included in order to provide sufficient spacing for a following vehicle to come to a complete stop without colliding with the vehicle in front if the leading vehicle performs a hard braking scenario, or emergency stop (23). Considering the differences automation will introduce to reaction time, as well as the differences

electric vehicles will introduce to acceleration/deceleration and braking capabilities, the inter-vehicle spacing may be significantly reduced from conservative values considering manually controlled ICE vehicles.

These models are applicable to cases where each vehicle in the traffic stream maintains the same (or nearly the same) constant speed and each vehicle is attempting to maintain a consistent spacing (e.g. “steady-state”), they are appropriate for automated vehicle applications as well.

Car Following Model Development

Single lane car following models assume a correlation between vehicles within a range of inter-vehicle spacing. Each driver in a following vehicle is an active and predictable control element in the driver-vehicle-infrastructure system and requires a continued response to a continuous series of stimuli. The relatively simple task of one vehicle following another on a straight roadway where passing is prohibited has been categorized by three subtasks (23):

1. Perception: The driver collects relevant information primarily from the motion of the lead vehicle and the driver’s vehicle. This includes vehicle speeds, accelerations/decelerations, inter-vehicle headway spacing, and rate of closure.
2. Decision Making: A driver interprets the perception information obtained within a framework of knowledge of vehicle characteristics and from the driver’s experience. The integration of current information and catalogued knowledge allows for the development of driving strategies that become “automatic” and from which evolve “driving skills.”
3. Control: The skilled driver can execute control commands with dexterity, smoothness, and coordination, constantly relying on feedback from their own responses.

For automated vehicles, this model will be similar; however, key differences exist in the perception and decision making subtasks. Rather than keeping a following distance that a human driver feels is safe, automated vehicles perform the perception subtask using sensing and communications technologies (V2V/V2I). Therefore, vehicle speeds, accelerations/decelerations, inter-vehicle headway spacing, vehicle dynamics and performance measures will be sensed and/or communicated by the vehicles. Specific algorithms for interpreting this information according to the vehicle characteristics of both the leading and following vehicles will be needed for the decision making subtask. This process represents a “reaction time,” or total delay in terms of a response to a continuous series of stimuli for car following and is illustrated in Figure 4.

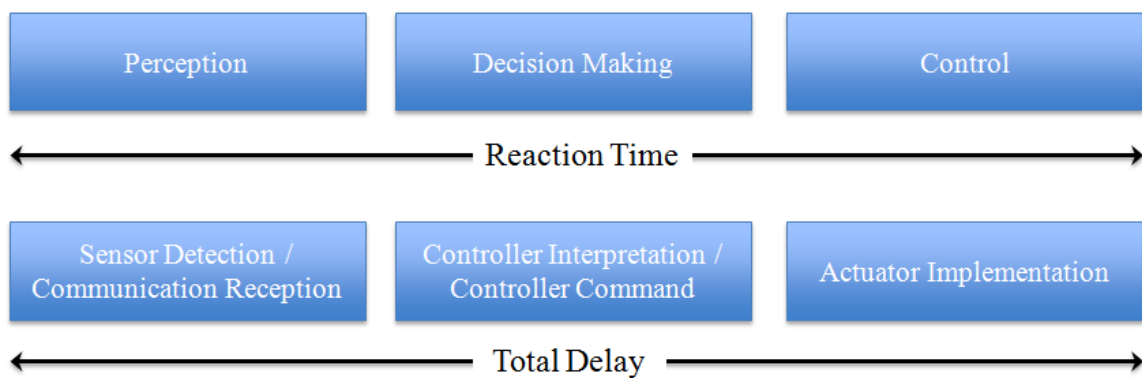


FIGURE 4. Human Reaction Time vs. Automated Delay.

Microscopic/Macroscopic Models

Microscopic models can be used to determine the velocity, flow, and density of a traffic stream when the traffic stream is moving in a steady state. Considering two consecutive vehicles on a single lane of a highway, as shown in Figure 5, the leading vehicle is considered to be the n th vehicle and the following vehicle is considered the $(n+1)$ th vehicle. The distances of these vehicles from a fixed point at any time, t , can be taken as x_n and x_{n+1} , respectively.

The general expression for the microscopic models has been written by Garber and Hoel (29) as:

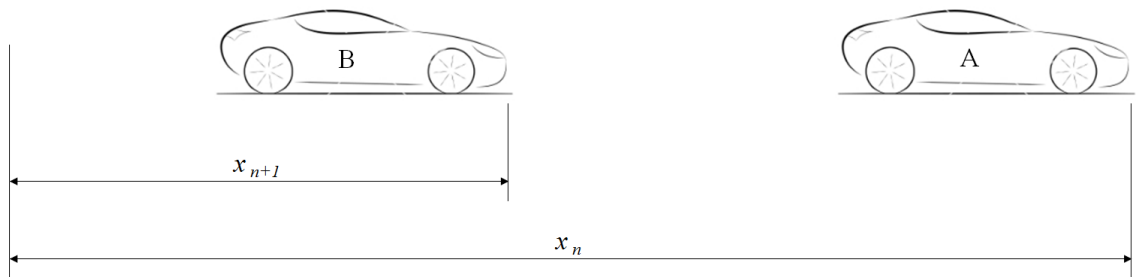


FIGURE 5. Basic Assumption of Car Following Theory.

$$\ddot{x}_{n+1}(t + \tau) = a * \dot{x}_{n+1}^m(t + \tau) * \frac{[\dot{x}_n(t) - \dot{x}_{n+1}(t)]}{[x_n(t) - x_{n+1}(t)]^l} \quad (2.3)$$

where

\ddot{x} = acceleration, [feet per second squared, ft/s²]

\dot{x} = velocity, [feet per second, ft/s]

τ = time lag of response to the stimulus, or reaction time, [s]

$a, l,$ and m = constants

Using this general expression for microscopic models, macroscopic models may also be obtained analytically. Garber and Hoel (29) further show that the macroscopic traffic flow model known as the Greenberg model is obtained when $m = 0$ and $l = 1$. The well-known Greenshields' model can similarly be obtained when $m = 0$ and $l = 2$.

Gipps' Car Following Model

The car following model used in many microscopic simulation packages is known as Gipps' model. In this model, certain characteristics of each vehicle are calculated for each pre-determined time-step. Hence, the model is a discrete time, continuous space model. The primary quantity that is calculated is the vehicle's speed, and through this, its new position. The formula used to calculate the updated speed (at time $t + \tau$) was modified using the equation shown by Spyropoulou (30), and is shown in the following equation:

(2.4a)

$$u_{n+1}(t + \tau) = \min \begin{cases} F(t) \\ G(t) \end{cases}$$

where

(2.4b)

$$F(t) = u_{n+1}(t) + 2.5a_{n+1}\tau \left(1 - \frac{u_{n+1}(t)}{U_{n+1}}\right) \sqrt{0.025 + \frac{u_{n+1}(t)}{U_{n+1}}}$$

(2.4c)

$$G(t) = b_{n+1}\tau + \sqrt{b_{n+1}^2\tau^2 - b_{n+1} \left[2(x_n(t) - l - h - x_{n+1}(t)) - u_{n+1}(t)\tau - \frac{u_n(t)^2}{b_n}\right]}$$

and

u = speed, [ft/s]

a = maximum acceleration which a driver wishes to undertake, [ft/s²]

τ = time lag of response to the stimulus, or reaction time, [s]

U = speed at which a driver wishes to travel, [ft/s]

b = most severe braking a driver wishes to undertake ($b < 0$), [ft/s²]

x = distance from a fixed point, [ft]

l = average effective vehicle length, [ft]

h = average space headway distance from the front bumper of following vehicle to the rear bumper of leading vehicle, [ft]

The formula for the estimation of a vehicle's speed comprises of acceleration and deceleration states. The speed that a vehicle would obtain if its movement were not impeded by the movement of a preceding vehicle is given by Equation 2.4b. The speed that a vehicle would obtain if its movement were impeded by the movement of a preceding vehicle is given by Equation 2.4c. Generally, if the limiting condition for vehicles in a link is Equation 2.4b, this indicates that vehicles are moving at free-flow speeds, whereas if the limiting condition is

Equation 2.4c, this indicates that the link is congested. However, for automation purposes, rather than indicating congestion, Equation 2.4c may indicate the existence of a platoon.

Finally, the new position of a vehicle at time $(t + \tau)$ was also shown by Spyropoulou (30) in the following equation:

$$x_{n+1}(t + \tau) = x_{n+1}(t) + 0.5[u_{n+1}(t) + u_{n+1}(t + \tau)]\tau \quad (2.5)$$

where

x = distance from a fixed point, [ft]

u = speed, [ft/s]

τ = time lag of response to the stimulus, or reaction time, [s]

Although these equations were developed assuming human drivers controlling vehicle movements, through vehicle automation, the values of certain parameters (i.e. τ , h) will be different, thus producing different results. For example, although the inter-vehicle headway spacing will be dependent on communications/sensing capabilities as well as the vehicle performance measures of both the leading and following vehicles, much tighter inter-vehicle spacing within vehicle platoons could be achieved through automating the driving task. Safely maintaining these tighter spacings will theoretically lead to significant increases in capacity, as shown by previous research, and can potentially lead to significant impacts in operational efficiencies.

Vehicle Automation

Although vehicle automation may seem like a “futuristic” concept, the idea has been around for centuries. Leonardo da Vinci considered the idea of a self-propelled, automated vehicle in the 15th century, where the vehicle’s direction was determined by the configuration of its springs and gears, rather than by a steering wheel (31). In 1939, at the World’s Fair in New

York, General Motors (GM) sponsored an exhibit called “Futurama” – considered by some to be the model for the modern interstate highway system. The purpose of the exhibit was an attempt to design the world 20 years into the future. Among many ideas and concepts, it included automated highways and suburbs (32). A similar exhibit was again displayed at the 1964 World’s Fair in “Futurama II.”

However, research and development in automated highway systems did not begin until 1986, when the University of California Berkeley’s Partners for Advanced Transportation Technology Program (PATH) began the Automated Highway Systems (AHS) project. This project’s system relied on V2V and V2I communication, as AET will. In 1997, the National Automated Highway System Consortium (NAHSC) was formed with the ultimate goal of identifying a feasible full automation concept. Demo ‘97 was thus an automation concept of a short platoon of automated vehicles traversing themselves down a stretch of Interstate-15 in San Diego, California (33). Focus was later also turned to busses and other heavy-vehicle applications (34, 35).

Automated vehicle control may be achieved in a variety of ways. In Demo ‘97, lateral control was achieved using magnets imbedded in the roadway (36). Today, lateral control of a vehicle may be achieved using magnets, as in Demo ‘97, the use of sensors or video cameras to track visual lane boundaries (white or yellow painted road markers), or the use of Differential Global Positioning Systems or Inertial Navigation Systems (37). The same would also be achievable through V2I and V2V communications. V2I data may include information such as lane widths, roadway geometry, and precise real-time vehicle location and position information.

Longitudinal control (acceleration/deceleration) of the vehicles in Demo ‘97 was achieved using radar and other sensors (36). Today, technologies in advanced cruise control and collision avoidance systems further strengthen the feasibility of automating the longitudinal control of a vehicle. Further utilizing V2I/V2V communication, speed adjustments and traveling

maneuvers may be communicated and automatically accommodated. This process would eliminate many common human errors of driving, such as failure to check a blind spot, as well as having to quickly apply the brakes due to another vehicle unexpectedly maneuvering into another lane. As a result, safety may be expected to significantly improve, and non-reoccurring congestion has the potential to be significantly reduced.

By communicating location and driving conditions between vehicles and the infrastructure, critical data may also be passed to vehicles upstream of a given point at both short and long distances. For example, a lead vehicle communicating to other following vehicles and the infrastructure that the road is slippery allows the platoon to adjust its speed accordingly. Also, when the next platoon of vehicles is not close enough in proximity to achieve V2V communication, the V2I capabilities can also be used to inform the next platoon that adverse roadway surface conditions exist ahead. That platoon may then adjust accordingly, thus reducing the risk of an incident. Upcoming impedances and lane closures are also examples of information that may be passed V2I, which has the potential to significantly reduce traffic congestion issues as well. Therefore, with AET addressing reoccurring and non-reoccurring congestion, more consistent traffic flows may be achieved, and roadway efficiency would significantly increase, particularly on roads with high demand.

Automatically adjusting vehicle travel according to the information provided by the V2V/V2I data transfer also has potential to reduce the AET vehicle's energy consumption. Communication allows vehicles to safely narrow the headway spacing between them while maintaining consistent speeds, thereby allowing vehicles to travel in tight platoons. The "drafting effect" created would reduce aerodynamic drag for follower vehicles, thus reducing the amount of energy required to power a vehicle along its path.

Finally, lane capacity may be significantly increased by reducing the headway spacing, increasing traveling speeds, and narrowing lane widths. This is especially significant for

locations with right-of-way limitations. Increasing throughput per lane and adding additional lanes without having to physically expand the roadway represent significant motivations for the development of an automated system.

According to an NAHSC report (36), the theoretical capacity of a dedicated automated highway lane was estimated around 8,000 vehicles per hour per lane (vphpl). Among the assumptions in this calculation were sensing delays, emergency warning signal output and detection delays, nominal actuation delays, and actual braking trajectories for a typical passenger vehicle with an internal combustion engine (ICE). The total “reaction time” of an autonomous or cooperative vehicle was estimated to be between 300 and 350 milliseconds, excluding the actual braking trajectories.

A comparison of human and automated measured brake reaction times is shown in Figure 6. The figure shows 85th-percentile values, when an event is expected, human reaction time averages about 0.6 seconds, with a some drivers taking as long as 2 seconds. With unexpected events, reaction times increased by 35% (38).

The mainline capacity of a roadway is affected by the traffic operations of entering vehicles on that system. Traditionally, freeway entrance processes have been studied in the

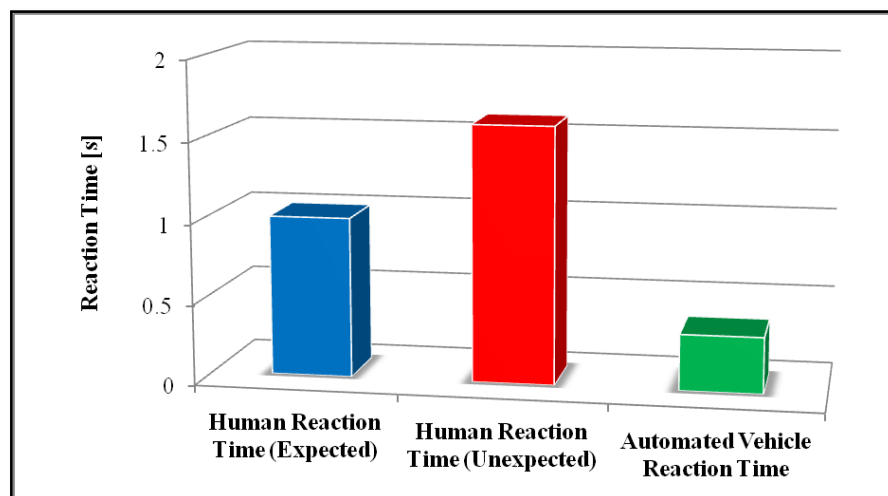


FIGURE 6. 85th-Percentile Reaction Times.

context of driver behavior, with respect to acceleration/deceleration and gap acceptance behavior (39, 40). However, an AET system will not perform these procedures according to typical parameters, as vehicles will be under automated control. Despite that fact, the effect of entry operations on traffic flow must not be overlooked when estimating the true theoretical capacity of an automated freeway lane.

As part of the AHS project, several entrance and exit configurations for automated vehicles were examined (5). Two alternatives were specified in some detail, including configurations where entry and exit occurred through a “transition lane” separating manual from automated lanes, and where entry and exit occurred through dedicated “ramps.” However, both configurations mentioned the need for accommodations for rejecting unqualified vehicles during the check-in phase and handling non-responsive vehicles during the check-out phase, yet no accommodations were specified. Considering the assumptions made in the report, the overall mainline (“steady-state”) capacity of an automated lane was calculated to be approximately 8,250 vphpl. Assuming entry and exit configurations, mainline flows, even below capacity, were reduced by about 10% (from 6,000 vphpl to 5,400 vphpl).

Other research on automated lane capacity has examined the total highway capacity as well as the delays that occur at automated entrances (41, 42). Required on-ramp capacity as a function of the on/off ramp spacing, in order to support a total automated highway capacity of 16,000 vehicles per hour (vph) was determined. Nominal mainline capacity of an automated lane in this report was estimated to be approximately 8,372 vphpl. Assuming various entry protocols, this capacity was reduced by percentages ranging from 25% to 75%.

Therefore, it is clear that despite vehicle automation and the communicative advantages transportation operations have available today, capacity will be affected by the number and type of interruptions in traffic flow made by merging vehicles. Optimal strategies must be identified

in order for vehicle automation to begin its implementation. The research presented in this thesis will differ from previous efforts by modifying entry/exit configurations as well as updating protocols related to the merging strategies for automated vehicle travel.

CHAPTER 3

TRANSITION STRATEGY AND MODEL DEVELOPMENT

One of the major challenges for AET is changing the way people travel, including the penetration rate required to achieve system-level benefits. In order to realize those benefits, barriers, including the logistics of a deployment strategy in transitioning from today's transportation system to an AET system, must be addressed. Previous work in highway automation (3) has addressed many of the issues concerning vehicle automation, but lacks the added benefits of vehicle electrification. This strategy is meant to add to those efforts previously made.

In order for AET to succeed in implementation, a logical transition strategy must exist which encourages the development of necessary technology in both vehicle and infrastructure. Similarly, supply and demand must be stimulated through this strategy such that it encourages further development and widespread adoption.

Drawing from history, previous attempts at system-level changes in the transportation sector have ultimately failed in part due to an inability to provide backwards compatibility to previous systems (2). When the Federal-Aid Highway Act (43) was enacted, creating what is now known as the Interstate Highway System, President Dwight D. Eisenhower simply sought an increased ability to quickly move military resources across the country (44). While this system ultimately led to monumental changes in vehicle and infrastructure technology, it was primarily developed simply to increase mobility for existing vehicles.

It may be argued that this compatibility, along with the potential for its adaptation to upcoming technological advances in transportation, were some of the chief reasons for the success of this system. As the nation developed around it, it also provided direct user benefits by offering easy access to goods and resources from further distances. These benefits thus

stimulated demand, and consequently supply, of further developments in transportation technology both in vehicle and infrastructure that still continues today. Therefore, this same model should be used as a template in developing future transportation system options.

Examining the vehicles on roadways today, the energy that powers them is almost exclusively produced by the burning of gasoline in an ICE. Government requirements for reduced emissions and improved fuel economy have therefore become stricter. Travelers have also increased their demand for more environmentally friendly and higher fuel economy vehicles (45). Also, considering the continued efforts to increase transportation safety, technologies aiding in safety and convenience, including partially automated vehicle control features (i.e. obstacle detection, adaptive cruise control, lane keeping assistance, and connected vehicles), are found in many current vehicle systems and will continue to be developed.

Therefore, using the model of the past, this information may be used as a starting point for developing a successful transition strategy to move from today's transportation system to a future AET system.

Stationary Charging

Embracing the current environmental "green boom" and anticipating its growth specifically in electric vehicles represents the first stage of the transition strategy. The most stable, and the most "practice-ready" application of wireless electric power transfer for vehicles lies in stationary charging.

Personal Application

The most obvious first application for stationary charging is for personal home use. This includes the installation of wireless charging pads at one's home – in the garage or driveway. Rather than using a plug-in cord to transfer energy directly from grid to vehicle, the power is connected to wireless charging pads on or underneath the pavement. When a vehicle with

compatible technology comes within an acceptable range to allow for a safe and efficient power transfer to occur, the vehicle's battery is charged automatically. This provides direct benefits to users by eliminating the need to plug in their vehicle. This benefit may be significant in marketing strategies, due to the fact that when this task is ignored or forgotten, the range of an electric vehicle is diminished. With wireless "eParking," drivers can simply park their car and forget about worrying about having a fully charged battery the next time they need to travel.

Public Applications

The next step of the transition strategy is to expand the user benefits of electric vehicles. For example, in an effort to promote the adoption of green vehicles, Salt Lake City currently offers free metered parking to vehicles meeting any one of the following conditions (46):

1. The vehicle has a Utah Clean Fuel special group license plate displayed.
2. The vehicle achieves 41+ miles per gallon (MPG) city fuel economy as determined by the EPA.
3. The vehicle is certified as achieving an EPA pollution score of at least 8 in Utah.

Retail businesses offering priority parking spaces for green vehicles would also promote the adoption of electric vehicles.

However, current electric vehicles suffer from range limitations on how far they are able to travel between recharging their batteries. While some vehicles address this issue by including energy-generating designs (i.e. regenerative braking (47)), none of them are able to produce enough energy to resolve this issue completely. As a result, the adoption of electric vehicles by the public has been slow, as they are not likely to sacrifice their current freedoms in mobility, despite the economic and environmental gains.

Therefore, further expanding the benefits of electric vehicles, the next step of the transition strategy lies in extending wireless charging technologies to public applications where

drivers frequently stop their vehicle (i.e. parking garages, street parking, and retail business parking lots). Tax incentives could be offered to retail businesses for the installation of eParking, similar to the private application. These priority parking spaces would be reserved specifically for vehicles with wireless power transfer capabilities.

This step of the transition strategy begins to eliminate range anxiety by providing convenient intermediate charging points. Thus, by regaining freedoms in mobility, as well as gaining the economic and environmental benefits an electric vehicle offers, public adoption for electric vehicles would be stimulated.

Semi-Stationary Charging

This stage of the transition strategy attempts to further resolve range anxiety for electric vehicles by adding the ability to charge at locations where vehicles momentarily pause their vehicle en-route. This is specifically beneficial to agencies in control of vehicle fleets that frequently use the same locations to pause throughout their route.

Private Applications

For private applications, loading docks, for example, present potentially ideal locations for implementation in this step of the transition strategy. Freight vehicles will have the ability to recharge their batteries as cargo is loaded and/or unloaded. Depending on the amount of time spent for this process and the amount of energy capable of being transferred during that time, freight vehicles could potentially eliminate or reduce the costs of re-fueling, including time spent off-line and the cost of fuel.

In addition to electric power transfer technology, off-road applications for automated vehicle technology may begin to emerge at this stage of the transition strategy. Ports and mining facilities, for example, could benefit from automating and electrifying short vehicle trips across dedicated travel paths.

Public Transportation Applications

Public transportation applications present potentially ideal locations for semi-stationary charging. Taxis, for example, frequently wait for passengers at designated locations at airports, public transit stations, and hotels, often times waiting for long periods of time. Upon gaining passengers, a taxi will take them to their destination and return again to a location where they may acquire more passengers. Incorporating wireless charging capabilities at these locations where taxis wait for passengers may motivate agencies in control of taxi fleets to convert to electric vehicles. Benefits to this conversion can be seen in reduced idle costs, reduced needs to refuel a vehicle, and reduced maintenance costs.

Buses also present ideal applications at this stage of the transition strategy, as they travel along specific routes in a closed loop. They begin from one point and travel along a designated route, making necessary stops along the way at designated locations, and return again to the point of origin. Installing charging pads at bus stops would allow vehicles to gain “mini-charges” during the boarding and alighting stages of a stop, allowing vehicles to regain all, or at least portions of the power lost between stops. Potential benefits a transit agency may see upon the adoption of a wireless electric bus fleet include:

- Decreased fleet sizes as a result of reducing or eliminating the need to take vehicles off-line to refuel or recharge
- Increased vehicle efficiency due to decreased vehicle weight as a result of smaller battery requirements
- Decreased operational costs due to the fact that electricity is cheaper than gasoline
- Decreased maintenance costs due to the fact that electric motors are cheaper and easier to maintain than combustion engines
- Possible tax incentives for “going green”

As a point of note, currently, specific bus routes in Logan, as well as Salt Lake City, Utah are scheduled for implementing stationary charging capabilities for fully electric buses (48).

Dynamic Charging (Charge-In-Motion)

The next stage expands upon the idea of semi-stationary charging and takes full advantage of the potential that wireless electric power transfer offers. This means moving beyond stationary charging and on-board storage to dynamic charging, where delivering electric energy on demand to moving vehicles will allow them to “charge-in-motion.” However, stakeholders are unlikely to invest in charge-in-motion electric road infrastructure that will serve only small portions of the population and gain little benefits to the system as a whole. Therefore, implementation of this stage of the transition strategy is not likely to occur unless sufficient adoption rates have been achieved.

eLanes

In order to continue promoting the adoption of green vehicles, besides offering parking benefits, travel benefits have also been extended in many states. Virginia, for example, has lifted the high occupancy vehicle (HOV) restrictions for green vehicles to travel the HOV lanes (49). The designed benefit of an HOV lane is that it allows users to travel faster and free of congestion, while also freeing up congestion in regular lanes.

This stage of the transition strategy further promotes electric vehicle adoption specifically by incorporating wireless charging technology into an “eLane,” where travel is restricted to electric vehicles. In these lanes, series of charging pads, spaced closely together, would be embedded within the roadway infrastructure. As an electric vehicle with compatible technology comes within range of the first charging pad in the series to allow for a safe and efficient power transfer, the pad is activated, and electric energy is transferred to the vehicle. As the vehicle continues moving, it will eventually move outside the range of the first pad, and be within the

range of the next pad. The first pad is then deactivated, and the second pad is activated. This process continues as the vehicle traverses the eLane, and is illustrated in Figure 7.

With vehicles gaining a charge while traveling in this way, the roadway itself essentially becomes a charging station, thus allowing for a substantial increase in electric vehicles' range. In fact, by implementing charge-in-motion technology in major transportation roadways around the country, range-anxiety may be completely eliminated, urging widespread public adoption of compatible vehicles.

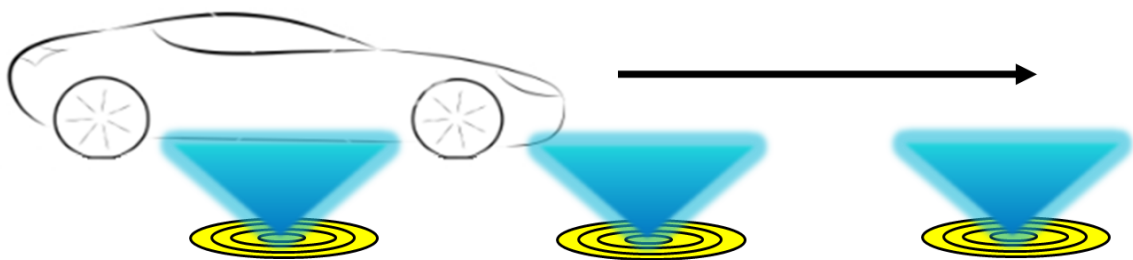


FIGURE 7. Charge-In-Motion Illustration.

Dedicated AET Lanes

As eLanes resolve concerns such as range anxiety and provide economic and environmental benefits on both individual and societal levels, human factors still limit the potential of this system. For example, one criticism of HOV lanes is that while HOV restrictions reduce congestion by encouraging carpooling, they also have the potential to amplify congestion by imposing increased congestion on the non-HOV lanes as well as decreasing the capacity of the HOV lanes themselves (50). If the combined penalties are larger than the positive carpooling effect, HOV restrictions actually worsen congestion. One of the reasons behind this phenomenon is the fact that an HOV lane effectively becomes a one-way single-lane highway whose speed is governed by low-speed vehicles. With human drivers still behind the wheel, even in dedicated eLanes, this phenomenon is likely to continue.

Therefore, at this point in the transition strategy, vehicle automation provides direct benefits to efficiency and safety. Further restricting travel in the eLanes to vehicles with automated control features would alleviate the issue of low-speed drivers governing the speed of travel in the AET lane. Traveling speeds would be unified, thus increasing roadway efficiency, and platoons could be formed, favoring energy efficiency and increased lane capacity. Vehicle automation would also ensure the most efficient power transfer from the charging pads, as a vehicle is guaranteed to pass over the pad in the center of the lane, where maximum power transfer occurs.

AET Nomenclature

In order to conduct meaningful discussions concerning Automated Electric Transportation, an understanding of key terminologies and nomenclature should be established. Therefore, the purpose of this section is to formally define that nomenclature. An AET Network is defined as the roadway infrastructure that incorporates wireless electric transfer pads capable of transferring the required energy to vehicles passing over them. It is further specified that all vehicles traveling on this infrastructure will be controlled automatically via wireless communication links between vehicles and the infrastructure. Therefore, the roadway infrastructure will be capable of sending and receiving information between itself and vehicles within a specified distance range. Other terms that may be used interchangeably include AET network, AET system, AET roadway, and AET lane(s). It is also recognized that these systems may be individual links to begin with, likely spanning commuter routes and other links that may alleviate traffic conditions. Later, these systems may be interconnected to span longer routes between major cities.

The term AET Vehicle refers to an automotive entity operating within an AET environment. While it is recognized that an AET vehicle may be “dual mode,” where it may also

be controlled manually while outside an AET environment, when it is operating within an AET system, it must be capable of utilizing the electric infrastructure described above, as well as meet performance standards with respect to automated longitudinal maneuvers (acceleration and deceleration), lateral maneuvers (lane keeping and lane changing), and communications (vehicle-to-vehicle, V2V, and vehicle-to-infrastructure, V2I). It is also noted that communications may also occur as infrastructure-to-vehicle, I2V, and infrastructure-to-infrastructure, I2I.

Within this AET structure, and with accurate communications and control protocol, one of the benefits of AET is the ability for vehicles to travel in tight platoons. A platoon is defined as a tight grouping of vehicles traveling together and interacting in a cooperative manner to maintain balance between objectives to maximize safety, maximize system capacity, and to meet individual travel needs. Interactions include maintenance of safe and efficient following distances through tightly matched performance of acceleration and deceleration maneuvers and maintenance of one-to-one and one-to-many situational awareness through frequent exchange of critical information packets on parameters of interest.

Two critical target following distances will exist within an AET system: intra-platoon spacing and inter-platoon spacing. Intra-platoon spacing, or the inter-vehicle spacing within a platoon, is defined as the target headway spacing a vehicle will maintain between itself and the vehicle directly ahead of it within a platoon. It is anticipated that this distance will be very short (on the order of 3-5 feet), depending on parameters related to speed, brake performance, controls, communications, and safety. However, the limits to intra-platoon following distance are governed by safety and aerodynamic advantage.

The minimum distance is determined based on the ability for a following vehicle to sense, interpret, command, and implement an emergency braking maneuver to avoid a serious collision with the leading vehicle under a condition where the leading vehicle executes an emergency braking maneuver. The maximum distance is determined based on the following

distance associated with loss of aerodynamic advantage associated with vehicle drafting for the purpose of achieving the minimum energy advantage associated with the break-even point determined in economic analysis of the AET alternative. These target following distances will be maintained by all vehicles within a platoon, with the exception of the first vehicle in the platoon.

Inter-platoon spacing is defined as the target headway spacing a vehicle will maintain between itself and the vehicle located in the rear of the platoon directly ahead of it. This distance will be greater than the intra-platoon distance, and it is anticipated that it will be on the order of 100 feet, depending on parameters related to speed, brake performance, controls, communications, maximum platoon size, and safety. However, the limits to inter-platoon following distance are governed by safety and capacity.

The minimum distance is determined based on the ability for a following platoon to execute an emergency-braking maneuver to avoid overrunning a platoon experiencing a catastrophic event that brings the leading platoon instantaneously to a velocity of zero. The maximum distance is determined based on the headway spacing associated with the minimum capacity advantage over a conventional freeway associated with the break-even point determined in economic analysis of the AET alternative. Only vehicles designated as the first vehicle in a platoon will maintain these following distances. Therefore, vehicles operating on an AET roadway will each have a specific role, determined by its position relative to other vehicles in the system. A vehicle can either be a Singleton, a Leader, or a Follower.

The term Singleton refers to the role of a vehicle within an AET environment that is operating outside of a platoon. It identifies a set of behaviors that a vehicle will follow in dynamic and static situations that involve joining an existing platoon or creating a new platoon while adhering to rules governing speed management, gap acceptance, platoon following, and itinerary management. A Singleton will always have a target headway spacing equal to the inter-platoon separation distance.

The term Leader, or Platoon Leader, refers to the role of a vehicle within an AET environment that is designated as the vehicle located in the front position of a platoon. It also identifies a set of behaviors that a vehicle will follow in dynamic and static situations that involve maintaining a platoon, joining an existing platoon, or expanding a new platoon while adhering to rules governing speed management, gap acceptance, platoon following, and itinerary management. A Platoon Leader will also always have a target headway spacing equal to the inter-platoon separation distance.

The term Follower refers to the role of a vehicle within an AET environment that is designated as any vehicle in a platoon that is not located in the front position of the platoon. It identifies a set of behaviors that a vehicle will follow in dynamic and static situations that involve maintaining a platoon, joining an existing platoon or expanding a platoon, and diverging from a platoon while adhering to rules governing speed management, gap acceptance, car following, and itinerary management. A Follower will always have a target headway spacing equal to the intra-platoon separation distance.

Model Development

As discussed, the implementation strategy will occur in piece-wise steps, especially beginning with locations identified as having the highest potential for positive impact and maximum exposure/usability. In addition, AET will not be a closed-loop system; therefore vehicles must have the ability of being driven both manually and automatically, suggesting a need for a check-in and check-out strategy. Fenton (51) discussed the likelihood that highways would be prime candidates for automation, while various rural roads and urban streets would not. Therefore, individual vehicles would enter the highway system at a designated entrance point where it would first undergo a rapid vehicle inspection, and the driver would indicate their destination. If the vehicle passed the inspection, it would move to an entrance ramp from which

it would be automatically merged into the traffic stream (check-in). The vehicle would then remain under automatic control until the driver's selected exit was reached; then it would be guided off the highway onto the exit ramp, and control would be returned to the driver (check-out).

Check-In

In this piece-wise implementation strategy, until a vehicle arrives at the beginning point of the dedicated AET lane, or "check-in" point, it would be driven manually, just as it is today (with the exception that it would be powered electrically). Upon check-in, the system must determine whether the vehicle attempting to enter the dedicated lane qualifies for its use. Allowing unqualified vehicles on the lane would defeat the purpose and benefit of the dedicated lane. Also, as this process must happen while in motion, the system must be fast and accurate in determining whether a vehicle qualifies for travel in the lane or not. Consequently, a rejection scenario should be anticipated and designed for in cases where vehicles may attempt to enter the lane, but do not qualify by either being a non-automated vehicle or an automated vehicle with substandard performance characteristics. It is also important to ensure that vehicles are switched to "automated" mode for entrance to be allowed. Just as unqualified vehicles on the dedicated lane would defeat the purpose and benefit of AET travel, qualified vehicles that are still manually controlled would do the same.

Finally, the process of merging into traffic flow on the AET lane would then be performed automatically. Acceptable gaps into which vehicles checking in to the system will fill must be calculated and evaluated for this process to successfully occur. Also, the traffic flow characteristics before and after a vehicle or group of vehicles check in should be carefully analyzed. This analysis would provide valuable insight into such aspects as the capacity of the AET lane and the suggested frequency of dedicated check-in interchanges.

Check-Out

Just as a vehicle checks in at the beginning of the dedicated AET lane, it must check-out when it reaches its end. One of the benefits of automated driving is that the driver is no longer required to pay attention to the driving task. Drivers would have the ability to use that time to perform other tasks valuable to each individual. These activities may range from sleeping, reading, watching movies or some other form of entertainment, or working on a computer. However, it would be disastrous if a driver was asleep or otherwise not aware or prepared to manually take over the task of driving, and they were suddenly required to do so.

Thus, the transition of control from automated to manual must also be explored prior to AET's implementation. However, while the importance of this process is recognized, for this thesis, the check-out process is suggested for future work and is only discussed for understanding here. This process relies on human awareness and ability. Therefore, before check-out, the awareness of the driver must be determined. Once the driver is alert and prepared to make the transition from automated control to manual control, the transition must be just as smooth as check-in. The driver, rather than the system, should likely perform this task in order to ensure that the driver is prepared to manually control the vehicle. Therefore, in the event that a driver fails the awareness test, or fails to manually take control of the vehicle, a strategy should also be developed in which this scenario is accommodated for in such a way that it does not disrupt traffic flow and may continue until the driver is adequately alert and prepared to perform the driving task.

Configuration Design

A simple schematic of a possible AET interchange design is shown in Figure 8. In this schematic, there are several detection zones with specific functions to make the check-in process (Zones 1-5) and check-out process (Zones 6 & 7) run smoothly.

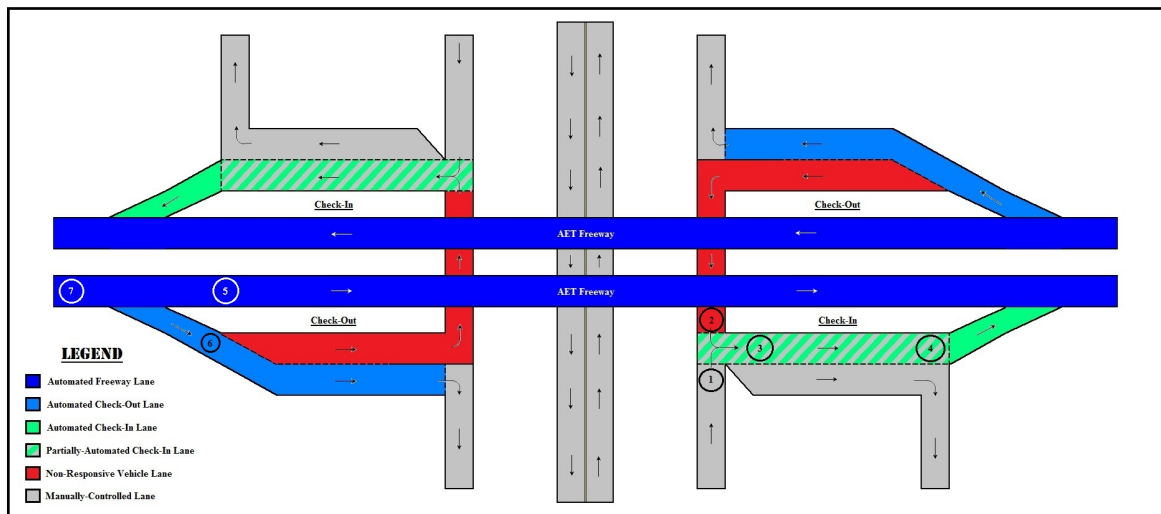


FIGURE 8. AET Interchange Schematic.

For the check-in process, Zone 1 would simply be an actuated signal for manually driven vehicles. This signal would show red unless a vehicle is detected. Zone 2 is similar to Zone 1; however no signal is needed due to the fact that vehicles will be under automated control at this point. The “signals” at Zones 1 and 2 would coordinate such that conflicts between vehicles would be avoided. Zone 3 would examine a vehicle’s specifications and qualifications to determine if a vehicle would be permitted to travel on the AET link. Unqualified vehicles are permitted to exit through the additional exit lane provided. Zone 4 would be an advanced actuated signal that would only give a “green” signal when a vehicle has been determined qualified for travel in the AET lane, the vehicle is set to “automated” mode, and an acceptable safe gap in which the entering vehicle may enter (determined by Zone 5) is detected.

For the check-out process, Zone 6 would determine if the exit ramp is clear for a vehicle to exit the AET link. Zone 7 would examine the awareness of the driver and their preparedness to take back control of the vehicle upon exiting. Vehicles with non-responsive drivers would be diverted off the AET link at the exit point and looped back around to the entrance for the opposite

direction. This process would repeat until a driver is aware and adequately prepared to assume control of the vehicle upon exiting.

CHAPTER 4

RESEARCH METHODOLOGY

This chapter presents the methodology for modeling and analyzing the AET mainline as well as an AET interchange. It includes research questions and hypotheses, basic model assumptions, equations for maximum capacity analysis, gap formation for the check-in process, a description of the entrance algorithm used, along with the equations involved in the analysis, and the performance measures used. Through this methodology, the requirements and impacts of traffic operations relating to the check-in, merging scenario at an AET interchange should be adequately understood.

Research Questions and Hypotheses

The major question on which this research focuses is: “In transitioning to an automated electric transportation system, what impacts will an automated vehicle interchange have on highway traffic operations?” As the transition strategy has been laid out, no further discussion on that matter will follow in this report. However, further details concerning the potential impacts of an AET interchange deserves further insight.

Hypotheses Related to AET Interchange Impacts

Through vehicle automation, lane capacities will likely be significantly increased. However, interrupting the traffic flow at interchange locations could negatively affect that mainline capacity. Nevertheless, if modeled properly, this impact may be reduced by identifying traffic operations procedures which will maximize mainline capacity and minimize or eliminate delays in mainline traffic.

Assumptions

In order to simplify the analysis of the model, specific assumptions will be made concerning vehicle and traffic characteristics. Vehicle characteristic assumptions will include those concerning vehicle length, communication abilities, acceleration/deceleration capabilities, and reaction times. For vehicle length, an average value for a mid-size sedan was used, which was 16.40 ft. In terms of communication, in order to establish the vehicle “roles” and maintain the proper following distances, as well as the most efficient platoon formation, vehicles should be able to use communicative devices to send and receive information between other vehicles.

This information should include data related to position (lateral and longitudinal), velocity, acceleration, and current headway spacing. Other information should include platoon identification, vehicle identification, vehicle role, platoon position, platoon size, desired exit, nearest desired exit by any vehicle in the platoon, and furthest desired exit by any vehicle in the platoon. It is possible for this information to be passed as a single string of numerical values. For example, the string could consist of a comma-delimited string correspond to the following:

- Vehicle Identification Number, [VIN]
- Longitudinal location, [GPS milepost position]
- Lateral location, [with respect to center, left = negative %, right = positive %]
- Speed, or velocity, [mph]
- Acceleration/deceleration, [feet per second squared, ft/s^2]
- Headway spacing, [ft]
- Platoon Identification Number, [PIN]
- Vehicle role, [1 = Singleton, 2 = Platoon Leader, 3 = Follower]
- Vehicle position within the platoon
- Total number of vehicles in the platoon

- Desired exit
- Nearest desired exit by any vehicle within the platoon
- Furthest desired exit by any vehicle within the platoon

Therefore, a vehicle with the communication string [...8704, 223.68, -0.01, 75, 1.20, 3.80, 1868, 3, 4, 8, 227, 225, 231] refers to a vehicle with VIN #...8704, located at GPS milepost position 223.68, with a 1% lateral deviation to the left of center, traveling 75 mph, accelerating 1.20 ft/s^2 , and with a current headway spacing of 3.80 ft. The platoon ID is #1868, the vehicle role is a Follower, being the 4th vehicle in an 8-vehicle platoon, desiring to exit the AET link at exit #227. The nearest exit desired by any vehicle within the platoon is exit #225, and the furthest exit desired by any vehicle within the platoon is exit #231.

This communication string is important because it allows an individual vehicle's position, velocity, and acceleration data to be processed in order to allow automated control with respect to other vehicles' data surrounding it in the network. It also allows for the possibility of forming platoons in the most efficient way. This is likely to be achieved by forming the platoons such that vehicles only diverge at their desired exits from the rear of their platoon, rather than splitting a platoon to allow middle vehicles to exit. For this application, it was assumed that this efficient platoon formation was already performed, such that platoons exist in configurations where exiting vehicles only exit from the rear of the platoon, and entering vehicles enter by prioritizing their entrance maneuvers by first, joining a platoon which has not yet reached maximum platoon size, and second, forming a new platoon. It was further assumed that vehicles are provided with perfect information via I2V and V2V communication concerning gap sizes in the mainline and the size of the platoon directly preceding that gap.

Further traffic characteristic assumptions will include those concerning mainline and ramp vehicle flows or demands. Due to the fact that pushing the lanes to capacity was the goal here, ramp demands were assumed to be large and constant. While this scenario may not entirely

represent the real world, it was simply assumed to analyze the worst-case scenario. However, for mainline traffic, capacity is a function of speed, platoon size, intra-platoon headway spacing, inter-platoon headway spacing, and car following logic.

Two of the major goals of AET are to increase the safety and capacity of our transportation infrastructure, particularly in freeway travel. In conjunction with these goals, AET proposes to accomplish these initially by the use of a single lane of traffic. In order to analyze the results of this system, a computer-based micro-simulation software package called Paramics was used with modified parameters to traditional car following protocol. Gipps' car following equations were used in this project, with parameters for maximum acceleration and deceleration set at levels acceptable for human comfort and safety. Liu and Wu (52) identify these levels to be approximately 6.56 ft/s^2 , while Li et al. (53) estimate approximately 8.2 ft/s^2 . For this research, $\pm 8.2 \text{ ft/s}^2$ were assumed for values of maximum acceleration and deceleration. The reaction time, or total delay for an automated vehicle in an AET environment was estimated at approximately 33.33 milliseconds (ms).

While automated lateral and longitudinal control will inevitably achieve safety increases by virtually eliminating the human factors of driving, the aspects of safety and capacity carry an inverse relationship. If each vehicle maintained a large enough headway spacing to be able to fully stop when the vehicle directly in front of it performs an emergency braking maneuver, where the leading vehicle abruptly decelerates to a velocity of zero without warning, capacity would approximate current freeway capacity. However, if all vehicles were to maintain a small headway spacing (small enough that in an emergency braking scenario, crashes may occur, but below the magnitude of causing serious injury), capacity would greatly increase on the order of four times current freeway capacities. However, this capacity increase consequently comes at some cost in terms of safety.

Therefore, there should be a balance between these two aspects in an AET system. As mentioned, two critical following distances exist: intra-platoon spacing and inter-platoon spacing. Previous research has indicated that under emergency braking scenarios, these critical following distances must maintain safety while also achieving acceptable capacity improvements (54).

Considering safety, automated vehicle platooning relies on the fact that intra-platoon separations must be safe, despite the short headway spacing, the steady state, or initial speed, communication delays, brake actuation delays, and brake performance. Safe short headway spacings can be explained by the fact that in an emergency braking scenario, vehicles following at very close distances will be close enough that there is not sufficient space to build a large enough speed differential before the vehicles collide to cause serious injury or damage. This “safe collision speed” concept was first introduced by Shladover (55), and expanded on by Tsao (56).

This distance should also be far enough away that any collision would be avoided under normal conditions, and limited even in emergency conditions. Preliminary results concerning safe following distances for identical electric vehicles traveling at speeds of 74.56 mph show that intra-platoon separations around 3.28 ft. and inter-platoon separations around 98.43 ft. may be considered valid assumptions for actual separation values, and resemble the values used by Fernandes and Nunes (57, 58) in their studies of autonomous vehicle platooning. These values were therefore used as constants for mainline speed, and intra- and inter-platoon headway spacings, respectively.

Equations for Maximum Capacity Analysis

Maximum or optimal capacity for AET is achieved when no interruptions in mainline flow occur. This value is important to calculate for the analysis of the effect the merging scenario imposes on the overall capacity of an automated system. Since it is initially assumed that each AET vehicle will be identical vehicle types, with identical performance characteristics and

uniform length, l [ft], if we take the intra-platoon headway spacing as h [ft], and the number of vehicles in a platoon as N [vehicles, veh], we can calculate the effective platoon length, L [ft], as:

$$L = l(N) + h(N - 1) \quad (4.1)$$

Then, with given information concerning the steady state travel speed, u [mph], and taking the inter-platoon headway spacing as H [ft], we can calculate the flow, Q [vph (per lane)], using the following equation. It should be noted that if N is considered the maximum platoon size, and all vehicles are traveling at steady state speed, the flow calculated is also the maximum capacity achievable on an AET freeway lane.

$$Q = N \left(\frac{1}{L + H} * u * 5280 \right) \quad (4.2)$$

Also, assuming Greenshields' speed/flow relationship, we can calculate density, k [vehicles per mile (vpm)], as:

$$k = \frac{Q}{u} \quad (4.3)$$

Gap Formation for Check-In

When a vehicle desires to travel on an AET link, it must perform the check-in procedure or entrance algorithm, which, in part, requires an analysis of gaps in the mainline traffic. Therefore, the formation of an acceptable safe gap merits further discussion. First, an acceptable safe gap is defined as a gap in the mainline that consists of an intra- or inter-platoon headway spacing before and after the vehicle (depending on the vehicle's position in the platoon), as well as the length of the vehicle itself.

The procedure for measuring this gap and releasing vehicles queued on the entrance ramp to merge into mainstream traffic will resemble that of an advanced ramp metering system. Liu (59) broadly divided ramp metering techniques into three categories: pre-timed, traffic-responsive, and predictive. In the traffic-responsive approach, detectors and computers are utilized to determine mainline flow and ramp demand in the immediate vicinity of the ramp, and an appropriate metering rate is set. However, within this approach, two basic schemes exist: flow-based and gap-based.

The gap-based scheme attempts to maximize the volume entering the freeway by looking for gaps in the main traffic stream. Upstream detectors, similar to those described previously in the model development, provide gap information to the ramp meter. For the check-in process, this scheme will be used to time the release of vehicles at the check-in point of the AET freeway, such that a released vehicle (or platoon) is guaranteed to find an acceptable safe gap upon arrival at the merge point on the mainline. One benefit to this scheme is that less land space is necessary, due to the fact that short acceleration ramps may be used (60).

In general, there are three cases for an acceptable safe gap to occur in the mainstream traffic. In these cases, gaps are assumed to occur naturally, so as to avoid any delay imposed on the mainline by forcing vehicles to brake in order to form gaps. The first is the case where there is light traffic on the mainline and there is demand on the entrance ramp. Once the vehicles on the ramp have been switched from manual mode to automated mode, they will immediately be allowed entrance to the freeway. The second case is moderate traffic on the mainline. In this instance, once a vehicle or group of vehicles on the on-ramp have been switched from manual mode to automated mode, they simply wait until they may enter the freeway such that they precisely meet the gap directly behind a vehicle traveling in the mainstream. Depending on the size of the platoon directly preceding the gap, these entering vehicles may either join at the rear of

the existing platoon on the mainline, or form a new platoon following the existing platoon on the mainline.

The third case is designed for high traffic volumes where mainline gaps are formed by exiting vehicles prior to the entrance ramp. Once a group of vehicles on the on-ramp have been switched to automated mode, they wait until they may enter the freeway such that they precisely meet the gap directly behind a vehicle traveling on the mainline. Depending on the size of the platoon directly preceding the gap, these entering vehicles may either join at the rear of the existing platoon on the mainline, or form a new platoon following the existing platoon on the mainline.

However, despite how the gap is formed, considering average flow values on the mainline, as well as average platoon sizes, previous research determined a value for an average gap in the mainline by the following modified equation (5):

$$\bar{G} = \left[\frac{3600(N)}{Q} * u * \left(\frac{5280}{3600} \right) \right] - N(l + h) + h \quad (4.4)$$

where

\bar{G} = average gap, [ft]

N = average platoon size, [veh]

Q = average mainline flow, [vph]

u = speed, [mph]

l = vehicle length, [ft]

h = intra-platoon headway spacing, [ft]

This equation was used in comparative analyses in order to show the improvement in effective capacity from past research.

Entrance Algorithm & Analysis Equations

Entrance into mainline automated vehicle traffic flow is a function of the gap size on the mainline, the size of the platoon preceding that gap, and the maximum platoon size. The logic behind the AET entrance algorithm is based on the concept that interrupting mainline traffic flow through the merging maneuvers of entering vehicles is unacceptable, as mainline traffic streams perform optimally under constant steady-state speed and spacing parameters. Therefore, the algorithm attempts maximize the size of all mainline platoons and fill all acceptable gaps in the mainline to the extent the ramp demand allows. Queued vehicles on the ramps are therefore allowed to enter as Singletons, or as platoons.

The algorithm resembles a gap-based advanced ramp metering system. It acts as a single server regulator for vehicles entering mainline automated traffic. Although ramp demand was assumed to be large and constant in order to push the system to capacity, the algorithm does account for scenarios where the ramp demand may be adjusted. A flowchart of the algorithm is provided in Figure 9 and the visual basic computer code for the algorithm is found in the appendix.

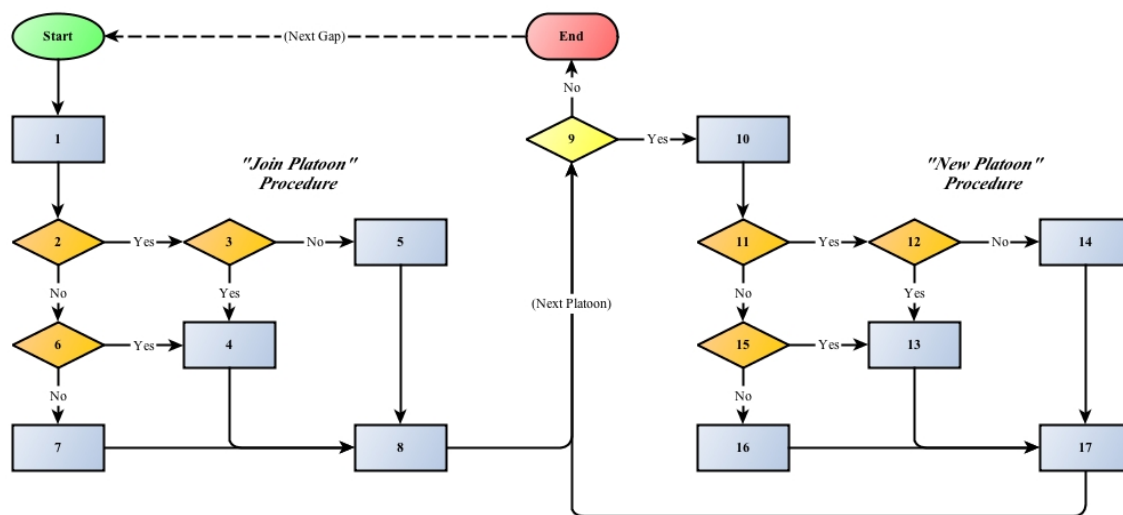


FIGURE 9. AET Entrance Algorithm Flowchart.

The algorithm consists of two parts: a “Join Platoon” procedure and a “New Platoon” procedure. In order to begin, a gap of at least the intra-platoon headway spacing (h [ft]), the length of a vehicle (l [ft]), and the inter-platoon headway spacing (H [ft]) must exist to start the algorithm. Therefore, the model requires pre-determined inputs for these parameters, as well as for the maximum platoon size (N_{max} [veh]). Once the algorithm starts, ramp demand (n_{Demand} [veh]) is detected on the ramp, and the preceding platoon size (N_p [veh]) and gap size (G [ft]) are detected on the mainline.

Also, initial values for the platoon number (i [platoons, pls]) and the total number of merging vehicles to be released for the current gap (n_{Total} [veh]) are set to 1 and 0, respectively. Setting i to a value of one simply means that the platoon on the mainline preceding the gap being analyzed is designated as the first platoon in the analysis. A “Join Platoon” procedure will determine the number of vehicles from the ramp that will be released to merge by joining this platoon, and, if space allows, a “New Platoon” procedure will determine the number of vehicles from the ramp that will be released to merge by forming new platoons following the initial mainline platoon.

The algorithm flowchart shown in Figure 9 was simplified to numbered junctions in the process for visual simplification. Verbal and mathematical definitions of each junction are described as follows:

1. Calculate the maximum number of vehicles that can fit into the gap, n_{Enter} [veh], assuming they perform the “Join Platoon” procedure. (Round down to the nearest whole vehicle.)

$$n_{Enter} = \frac{G - H}{l + h} \quad (4.5)$$

2. Does the maximum number of vehicles that can fit into the gap (n_{Enter} calculated in junction 1) exceed the number of vehicles required to fill the existing platoon to maximum size?

$$n_{Enter} > N_{max} - N_p \quad ? \quad (4.6)$$

3. Does the number of vehicles required to fill the existing platoon to maximum size exceed the demand on the ramp?

$$N_{max} - N_p > n_{Demand} \quad ? \quad (4.7)$$

4. Send the demand.

$$n_i = n_{Demand} \quad (4.8)$$

where

n_i = number of platoons released for platoon i , [veh]

5. Fill the existing platoon to maximum size.

$$n_i = N_{max} - N_p \quad (4.9)$$

6. Does the maximum number of vehicles that can fit into the gap (n_{Enter} calculated in junction 1) exceed the demand on the ramp?

$$n_{Enter} > n_{Demand} \quad ? \quad (4.10)$$

7. Send the maximum number of vehicles that can fit into the gap (n_{Enter} calculated in junction 1).

(4.11)

$$n_i = n_{Enter}$$

8. Determine the number of vehicles that will join the existing platoon, n_{Join} [veh]. Decrease the ramp demand by the number of vehicles that join the existing platoon. Store the count of the total number of vehicles released from the ramp for the current gap. Determine the size of the gap remaining, G [ft], after the entering vehicles join the existing platoon.

(4.12a)

$$n_{Join} = n_i$$

(4.12b)

$$n_{Demand} = n_{Demand} - n_i$$

(4.12c)

$$n_{Total} = \sum n_i$$

(4.12d)

$$G = G - n_i(l + h)$$

9. Is there any remaining demand on the ramp, and is the remaining gap large enough to allow any more vehicles to enter, assuming they perform the “New Platoon” procedure?

(4.13a, 4.13b)

$$n_{Demand} > 0 \quad \mathbf{AND} \quad G \geq 2H + l \quad ?$$

10. Calculate the maximum number of vehicles that can fit into the remaining gap, n_{Enter} . (Round down to the nearest whole vehicle.)

(4.14)

$$n_{Enter} = \frac{G - 2H + h}{l + h}$$

11. Does the maximum number of vehicles that can fit into the gap (n_{Enter} calculated in junction 10) exceed the maximum platoon size?

$$n_{Enter} > N_{max} \quad ? \quad (4.15)$$

12. Does the maximum platoon size exceed the demand on the ramp?

$$N_{max} > n_{Demand} \quad ? \quad (4.16)$$

13. Send the demand.

$$n_i = n_{Demand} \quad (4.17)$$

14. Send a platoon of maximum size.

$$n_i = N_{max} \quad (4.18)$$

15. Does the maximum number of vehicles that can fit into the gap (n_{Enter} calculated in junction 10) exceed the demand on the ramp?

$$n_{Enter} > n_{Demand} \quad ? \quad (4.19)$$

16. Send the maximum number of vehicles that can fit into the gap (n_{Enter} calculated in junction 10).

$$n_i = n_{Enter} \quad (4.20)$$

17. Determine the number of vehicles that will form a new platoon, n_{New} [veh]. Decrease the ramp demand by the number of vehicles that form a new platoon. Update the count of the total number of vehicles released from the ramp for the current gap. Store the number

of platoons that have been released. Determine the size of the gap remaining after the vehicles form the new platoon.

$$n_{New} = n_i \quad (4.21a)$$

$$n_{Demand} = n_{Demand} - n_i \quad (4.21b)$$

$$n_{Total} = \sum n_i \quad (4.21c)$$

$$i = i + 1 \quad (4.21d)$$

$$G = G - H - n_i(l + h) + h \quad (4.21e)$$

As soon as there is either no remaining demand on the ramp, or the remaining gap is not large enough to allow any more vehicles to enter, node number nine produces a “False” result, and the process terminates. Therefore, the analysis of the original gap is ended, and the output of the algorithm is the total number of vehicles released from the ramp, n_{Total} [veh], the total number of platoons released from the ramp, i_{Total} [pls], the remaining gap on the mainline, G [ft], and the remaining demand on the ramp, n_{Demand} [veh]. Information about each platoon released from the ramp is also obtained. This information includes the number of vehicles released to join the existing platoon on the mainline, n_{Join} [veh], the number of full platoons released (excluding the first and last platoons), n_{Full} [veh], and the number of vehicles released in the last platoon (excluding the first platoon), n_{Last} [veh].

This “release-to-gap” merging logic accomplishes the merging maneuver for automated vehicles without imposing any significant interruption to the mainline flow, as was proven by Ran et al. (6). Ran’s study explains that the consequence of prioritizing the mainline flow over the ramp flow in this way is that the mainline will be able to operate with minimal impact from the merging maneuver, which is the goal of this project. Thus, the algorithm developed

inherently gives priority to mainline flows, which in turn transfers any delay that would be experienced on the mainline from a merging maneuver to queued vehicles on the ramp. However, while delay may be transferred to the ramp, it should be noted that large ramp queues typically only develop under conditions of high mainline flows and few available gaps for merging. It stands to reason that under these conditions, mainline flows should take priority over ramp flows in order to move larger volumes of traffic.

Performance Measures

The performance measures used in this research were freeway and ramp lane capacities. This first includes the optimal capacity of the mainline without traffic interruptions. Next, taking check-in merging into account, ramp capacities for automated entrance ramps were assessed, followed by the effective downstream capacity of the mainline, including the merging strategy outlined previously.

CHAPTER 5

ANALYTICAL RESULTS

The results of this research include a working micro-simulation model of an automated merging strategy for vehicles in an automated electric transportation system. In addition, accurate estimates of lane capacities for automated vehicle systems both upstream and downstream of merging areas are calculated and proven. This analysis gives meaningful and measurable insight as to the potential benefits and requirements of an automated system.

Optimal Mainline Capacity

First, using the equations shown in the previous chapter, and assuming values of $l = 16.40$ ft, $h = 3.28$ ft, $H = 98.43$ ft, and $u = 74.56$ mph, Figure 10 shows the maximum capacity on the mainline of an AET freeway lane with respect to platoon size (N is varied) and compares it to a typical flow vs. density curve for a “normal” freeway lane. The term “Normal Case” here refers to a flow vs. density curve typically seen on today’s freeway lanes. It is re-emphasized here that this maximum value for AET capacity does not take into account any disturbances in mainline travel.

Next, in order to verify that the micro-simulation model accurately represented this maximum flow, a simple network consisting of a single lane of traffic with no interruptions was created in Paramics. As vehicles were generated, they would assume the car following logic described in this thesis and maintain the proper headway spacings, h and H . As the generation of the vehicles in the simulation was random, it was necessary to create a “dummy link” that was used for platoon forming purposes. In this dummy link, vehicles would travel at high speeds in order to “catch up” to the vehicle they would be following until they achieved the required spacing. After they had successfully formed and maintained their platoons for an acceptable amount of simulation time, they would then enter the “AET link,” where vehicle flows were

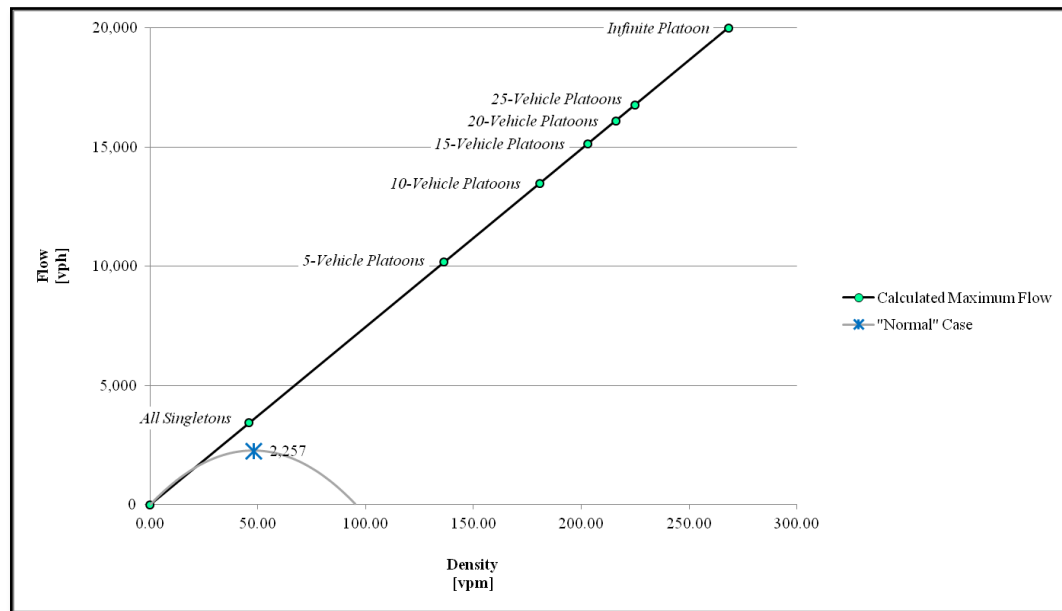


FIGURE 10. Maximum Mainline Capacity Flow vs. Density.

measured under platooned conditions.

It was anticipated that the simulated flows would match very closely with the calculated flows shown previously due to the fact that the speed and spacing of each vehicle in the model was under automated control. As is shown in Figure 11, this was found to be true. The vehicle flows under each scenario were exactly the same flows as the calculated results.

The usefulness of these values for optimal capacity is reflected in the growing concern of traffic congestion management where demand frequently surpasses supply, especially in locations where additional lanes are not viable options in terms of land space. Therefore, based on the results presented here, the automated platooning of traffic streams presents immediate benefits, even at the “All Singleton” level due to the use of constant spacing and automated vehicle control. In classical models, freeway traffic flows above a critical density of approximately 50 vpm enter into a congested state, where vehicles travel closer together, but at lower speeds until traffic comes to a complete stop at a jam density of approximately 100 vpm. However, the results of the micro-simulation model verify that traffic flow under automated control is capable of

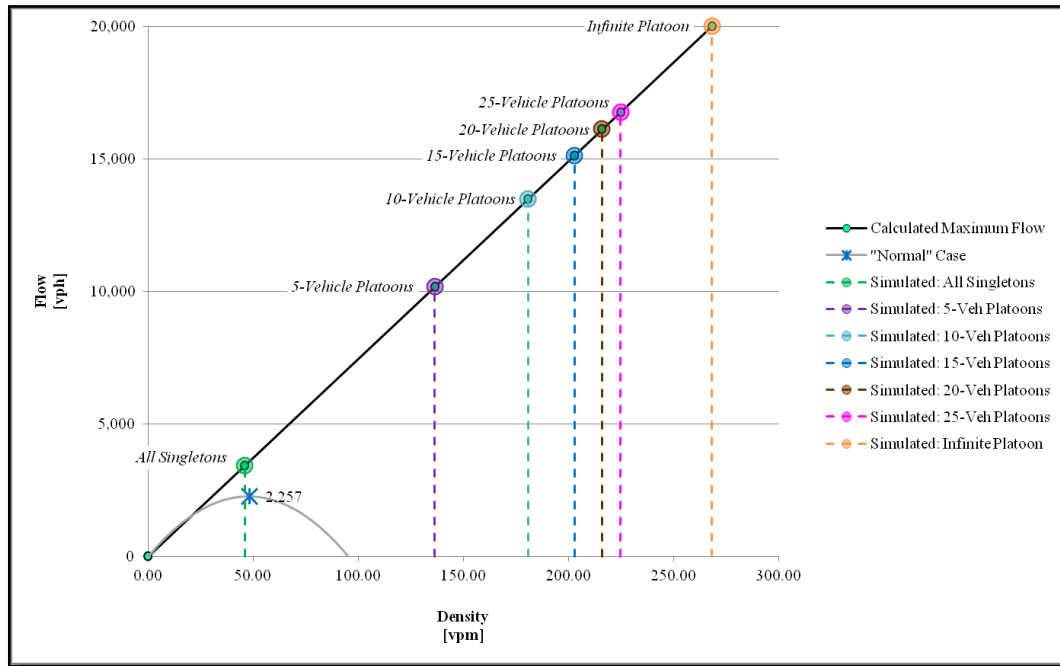


FIGURE 11. Simulated Results for Maximum Mainline Capacity.

achieving traffic flows at the upper bounds of “theoretical” optimal capacity. But in order for a traffic system to operate with a traffic flow at these upper limits, the admittance of vehicles to this system should be limited to ensure that the correspondent maximum density would never be surpassed (58).

Ramp Capacity

Using the merging strategy presented previously, the ramp flow is a function of the size of the gap in the mainline, the maximum platoon size, and the size of the platoon directly preceding the gap. As assumed in previous research, the average size of the gap in the mainline may be calculated as a function of the speed and flow rate of the mainline vehicles using Equation 4.4. Taking this value as an input for the merging algorithm, and using values for maximum platoon size equal to five and varying the mainline flows, Figure 12 shows an illustrative example of the calculated ramp capacity. The “Mainline Capacity” line is calculated

by subtracting the actual mainline flow from the calculated optimal capacity for the given maximum platoon size, and is shown for reference. The ramp capacity should never exceed this line, as that would cause the freeway to exceed maximum density, thus creating negative shockwaves that would impose delay on the mainline traffic flow.

As the size of the platoon preceding the gap on the mainline will vary stochastically from one to the maximum platoon size (in this case five), the ramp capacity was calculated for each case. While the results for uniform platoon sizes of 1, 3, and 4 are shown for reference, the solid black line in the figure represents the average for all cases, and can be taken as an average estimate of the ramp capacity at any given mainline flow. Under low mainline flows, the results show that the ramp capacity can be very high, as the mainline is free to accept large flows of vehicles from the ramp without interruption. However, these values are only applicable assuming constant and large ramp demands in order to determine the capacity. Under normal conditions, although the ramp capacity may be high, actual ramp flows will likely be limited to the ramp

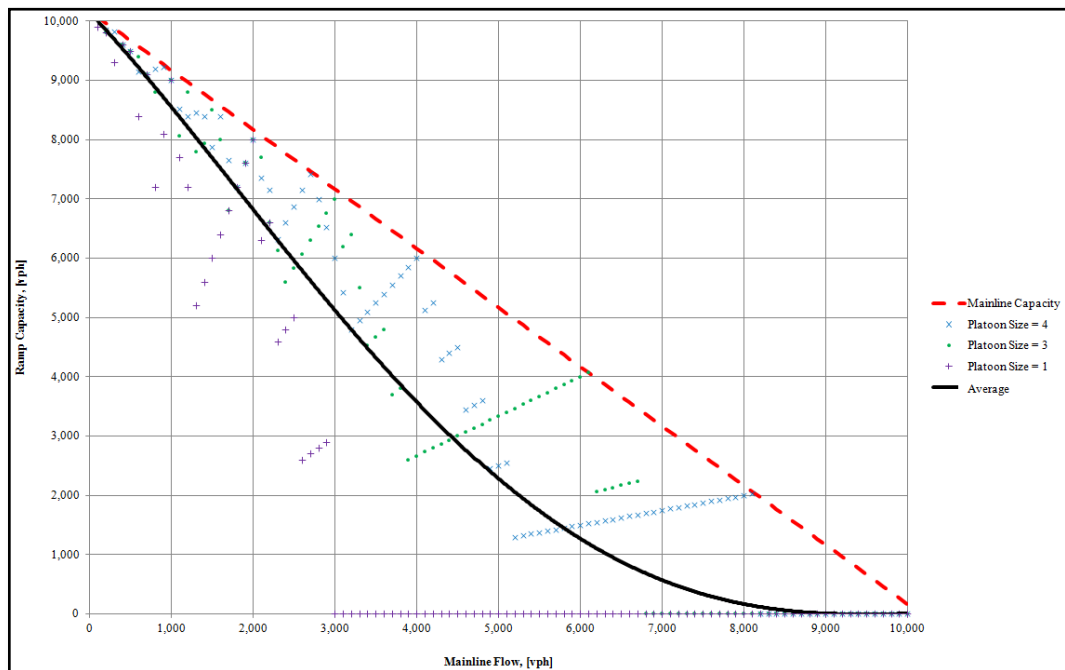


FIGURE 12. Ramp Capacity vs. Mainline Flow.

demand.

Conversely, under high mainline flows, there is a threshold where allowing merging vehicles is not acceptable without interrupting mainline flow, which would cause mainline vehicles and platoons to brake in order to allow merging vehicles to enter the freeway. As this scenario was determined to be unacceptable for this analysis, ramp capacity under these conditions is low, and eventually approach zero. It is acknowledged that this effectively gives priority to the mainline flow, which in turn transfers delay to the vehicles waiting on the ramp. While this may be true, at the small cost of delaying vehicles on the ramp, the mainline flows are able to operate with minimal impact from merging vehicles, thus maximizing mainline vehicle flow. The actual effect this has on mainline flows is explored in the discussion following on effective mainline capacity.

In order to verify this analytical analysis, the micro-simulation model was used to run multiple scenarios with varying mainline flows. Mainline flows in the model exist with stochastic variations in gap size and the size of the platoon preceding the gap on the mainline. This was achieved by seeding the demand in the simulation for each run. It was found that by following the merging algorithm for automated entry to an AET freeway lane, the simulation accurately represented both the mainline and ramp flows under high mainline flows. However, under low mainline flows, the simulation produced ramp flows slightly lower than the analytical model.

This was due to the fact that the ramp in the model was limited to two lanes, so as to more accurately represent a real-world on-ramp. Since there is a time lag between the time a platoon is released from the ramp and the next platoon on the ramp reaches the stop bar to analyze either the remaining gap or the next gap, some usable gaps in the mainline may pass by unused. This results in some capacity loss and was discovered while the scenarios were being analyzed using a single-lane on-ramp. Therefore, a two-lane on-ramp was then modeled, and the

results nearly doubled, as expected, with the addition of a second lane. It is anticipated that this trend would continue with the addition of multiple lanes on the on-ramp, however, these scenarios were not analyzed due to the fact that the flows achievable with two lanes were determined to be adequate with respect to the capacity loss and the land space required for additional lanes.

Therefore, rather than depicting the scenario for a ramp operating at maximum capacity, this phenomenon describes the model for the scenario of a ramp operating at flow levels corresponding to the actual demand at the ramp. Under these conditions, neither the ramp nor the mainline flows are expected to reach capacity, as the system lacks the required demand. However, through the merging logic presented in this research, operations under these conditions allowed the traffic flows to merge seamlessly, thus maximizing mainline and ramp flows.

Effective Mainline Capacity

While optimal mainline capacities and ramp capacities are useful tools in the analysis of an AET interchange, effective mainline capacity represents the merging of the two flows. The capacity of a merge or diverge area is always controlled by the capacity of its entering and exiting roadways (4). However, by monitoring and controlling the traffic operations and vehicle movements at these locations, turbulence due to typical merging maneuvers can be avoided, and thus the capacity of the roadways involved may be maximized.

When the vehicle speeds and headway spacings are controlled automatically through various communications and controls protocol, optimal mainline capacity can be broken down to the simple calculations shown in Equations 4.1 and 4.2. Then, using Equation 4.4 as well as the merging algorithm discussed, ramp capacity is broken down to basic gap acceptance theory. This section provides a comparative analysis of how this merging logic improves on past research,

focusing on the effective mainline capacity, or the capacity of the mainline at or directly downstream from an automated merging location.

Using Equations 4.1 and 4.2, the optimal mainline capacity was calculated with varying values for maximum platoon size and mainline steady-state speed. This was done to provide insight to moderate speed and high speed applications as well as optimal maximum platoon size. Clearly, if increasing optimal capacity was the only goal, longer platoon sizes provide more desirable results; however, considering safety and efficiency, especially relating to string stability of platooned vehicles, the analysis of a variety of platoon sizes aids in weighing options for various applications.

Table 2 shows the results of that analysis. These values represent the maximum achievable freeway lane flows for an automated system, given the parameters for speed, spacing, and platoon size, and represent the values that the merging logic should strive to achieve along the freeway.

Two trends recognized from this table are that as maximum platoon size increases, the optimal mainline capacity increases asymptotically to the infinite platoon case. The other is that as steady state speed increases, optimal mainline capacity increases linearly. Therefore, one can conclude that the benefits of increasing platoon size provide diminishing returns in terms of

TABLE 2. Optimal Mainline Capacity, [vph].

		<i>Speed, [mph]</i>				
		45	65	75	90	100
<i>Platoon Size, [veh]</i>	1	2,069	2,988	3,448	4,138	4,598
	5	6,137	8,865	10,228	12,274	13,638
	10	8,137	11,753	13,561	16,274	18,082
	15	9,128	13,185	15,214	18,257	20,285
	20	9,720	14,041	16,201	19,441	21,601
	25	10,114	14,609	16,857	20,229	22,476
	∞	12,070	17,434	20,116	24,140	26,822

capacity. However, increasing speeds continually provides added benefit, regardless of the platoon size. This may be especially insightful for research related to string stability for platooned vehicle formations and safety. If larger maximum platoon sizes can only produce limited improvements, efforts should be less focused on this factor and more focused on being able to safely control smaller platoons at higher speeds.

In order to perform a comparative analysis between past Automated Highway Systems (AHS) research and this current AET research, the same assumed values for spacing discussed previously in this report were used in all the relevant equations. Using the analysis equations and merging logic used in past AHS research found in (5), the average effective capacity was calculated as an average mainline flow at or directly downstream from the merge area of the freeway. This was obtained by finding the average flow for each maximum platoon size at increasing values of initial upstream mainline flow and preceding platoon sizes from one to the maximum value. Finally, an overall average for each case was calculated, the results of which are tabulated in Table 3. The values shown for the infinite platoon case were estimated based on the trend seen as maximum platoon size increased.

Again, it was observed that increases in maximum platoon size provided diminishing returns, asymptotically approaching the infinite case. Furthermore, it was observed that increases

TABLE 3. Effective Capacity (AHS), [vph].

		<i>Speed, [mph]</i>				
		45	65	75	90	100
<i>Platoon Size, [veh]</i>	1	1,458	2,096	2,139	2,729	2,937
	5	3,802	5,727	6,289	7,540	8,543
	10	4,832	7,226	7,872	9,532	10,757
	15	5,297	7,878	8,767	10,427	11,587
	20	5,476	8,022	9,055	10,776	12,121
	25	5,654	8,355	9,173	11,076	12,407
	∞	6,600	9,900	11,000	13,200	14,850

in steady state speed provided improvements in a nearly linear fashion. However, the results for effective capacity were considerably lower than the results for optimal capacity. This is due to the fact that the logic used in the AHS work does not utilize acceptable gaps in the mainline to their full potential. Also, in this past work, entering vehicles were permitted to impose delay on the mainline traffic stream. This delay was calculated, and efforts were made to minimize the imposed delay to less than a ten percent flow reduction. However, while this delay under conditions of low mainline traffic flow may not have been significant, it eventually increases exponentially under conditions of high mainline traffic flow.

Using the equations and merging logic described in this report, the same analysis was performed to determine the average effective capacity for an AET system. As was accomplished in the AHS analysis, the average effective capacity was calculated as an average mainline flow at or directly downstream from the merge area of the freeway. This was obtained by finding the average flow for each maximum platoon size at increasing values of initial upstream mainline flow and preceding platoon sizes from one to the maximum value. Finally, an overall average for each case was calculated, the results of which are tabulated in Table 4. The values shown for the infinite platoon case were estimated based on the trend seen as maximum platoon size increased.

Again, it was observed that increases in maximum platoon size provided diminishing

TABLE 4. Effective Capacity (AET), [vph].

		<i>Speed, [mph]</i>				
		45	65	75	90	100
<i>Platoon Size, [veh]</i>	1	1,926	2,823	2,916	3,621	3,975
	5	5,157	7,662	8,601	10,166	11,352
	10	6,973	10,375	11,470	13,775	15,442
	15	7,956	11,872	13,201	15,773	17,682
	20	8,579	12,777	14,230	17,025	19,125
	25	9,031	13,483	14,957	17,887	20,106
	∞	10,800	16,200	18,000	21,600	24,300

returns, asymptotically approaching the infinite case. It was also observed that increases in steady state speed provided improvements in a nearly linear fashion. Furthermore, the results for effective capacity using the AET logic were lower than the results for optimal capacity, although not as significantly as seen in the AHS analysis. This is due to the fact that the logic used in the AET merging algorithm fully utilizes the acceptable gaps in the mainline. Also, entering vehicles were not permitted to impose delay on the mainline traffic stream.

For a more clear understanding of the results seen in Tables 2 – 4, Figure 13 shows a graph of the results for optimal capacity, effective capacity using past AHS logic, and effective capacity using the AET logic presented in this report, all for the 75 mph case at each maximum platoon size (1, 5, 10, 15, 20, and 25). The results clearly show that the merging logic outlined in this report for AET improve upon what has been achieved in the past, especially as maximum platoon size increases.

While there remains a capacity loss using the AET logic, it is important to clarify that the capacity loss experienced using the AET logic is not the result of causing delay in the mainline.

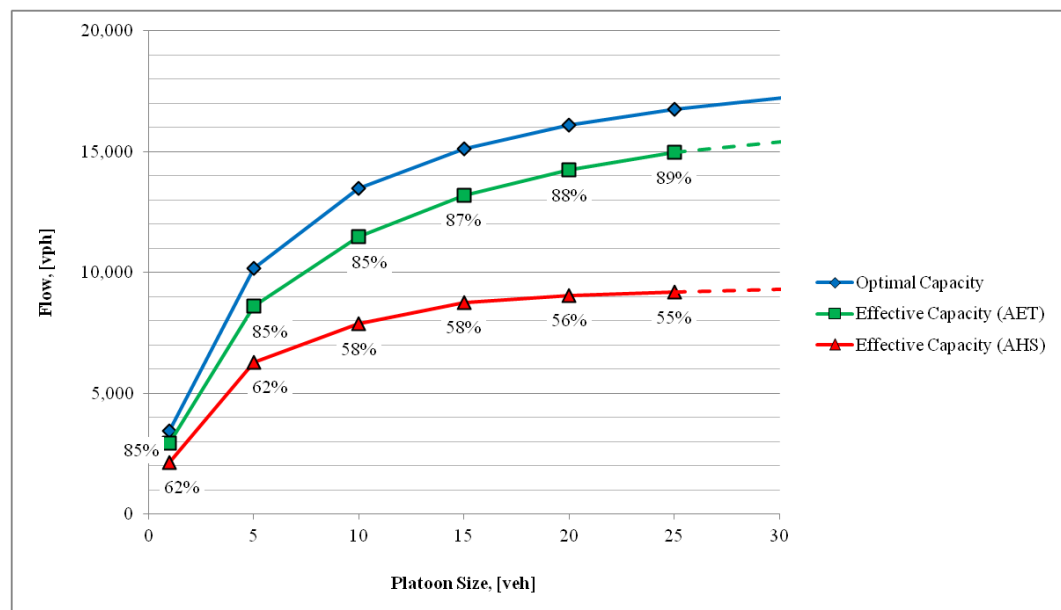


FIGURE 13. Capacity Comparison.

Rather, it is attributed to unused capacity. As the size of the gaps in the mainline varies stochastically, it is expected that not all gaps will be filled perfectly by merging vehicles or platoons. Therefore, some capacity will be lost due to this unused space. However, it is anticipated that this unused space, or this capacity loss, may be regained downstream by platoons re-assuming their optimum safe headway spacing. Thus, slight forward-moving shock waves may be seen in mainline traffic flows between interchange locations. Further analysis of the results shown by this research provide some additional insight relating to the transition strategy for automated electric transportation. The results shown for the low-speed scenarios provide information for policy makers and stakeholders in terms of the benefits that AET would provide in an urban setting. Major arterials that currently operate at speeds near 45 mph would see instant benefits in terms of capacity due to the fact that even with platoons operating as all singletons, a single lane of arterial roadway is capable of handling capacities only seen on freeways today.

The “All Singleton” scenario was chosen as an example for an urban setting due to the fact that arterial streets require more access points for entry and exit maneuvers than a limited-access freeway. Therefore, platooning may prove to be difficult, and if priority is always given to the major arterial as it was in the freeway scenario, it may also prove to be unfavorable in terms of entrance delay. However, under automated control, in addition to keeping constant spacing parameters, vehicles would also have the ability to safely increase steady state travel speeds. Applying this to the urban setting, capacity would then increase by nearly 1,000 vph.

For the freeway setting, the results of two scenarios can be compared to draw conclusions related to policy decisions concerning the operations of an AET freeway. The first is the scenario at 65 mph with a maximum platoon size of 10 vehicles per platoon. Referring to Table 4, the effective capacity under these conditions is just over 10,000 vph. The second is the scenario at 90 mph with a maximum platoon size of 5 vehicles per platoon. Again referring to Table 4, the effective capacity under these conditions is similar – just over 10,000 vph. Since the resulting

effective capacity is nearly the same, the difference between the two scenarios is the maximum platoon size and the steady state speed of the freeway.

Much research has gone into the investigation of linear platoons of vehicles (61, 62). It is recognized that as the number of vehicles in a platoon increases, string stability becomes more difficult to control. The consequence is that when string stability is lost, oscillations in intra- and inter-platoon spacing will cause degradations in safety and efficiency, and is unacceptable for an automated system. Therefore, in order to avoid this phenomenon yet still achieve freeway lane capacities above 10,000 vph, it may be wiser to set freeway operations at lower maximum platoon sizes, but increased steady state speeds.

CHAPTER 6

SUMMARY AND CONCLUSION

The importance of this work is propelled by the fact that after decades of use and deferred maintenance, the roadway infrastructure of this nation (in particular the interstate highway system) is in need of innovation. Our mobility, safety, health, prosperity, and security depend on reimagining, rather than repairing, that infrastructure. The subjects discussed in this thesis, including vehicle automation, energy transfer, and mobility, are becoming increasingly interdependent. Therefore, reimagining this nation's infrastructure has required looking at the big picture of how these different systems can work together to positively impact lives.

Recognizing that interconnectedness, AET's realization has the potential to revolutionize the way people move by providing unparalleled benefits to human health and safety, economic independence, and quality of life. With human error and vehicle emissions contributing to the vast percentage of the number of annual deaths directly related to motor vehicles, significant impacts could be achieved through the synergy of motor vehicle automation and electrification. AET has the potential of alleviating and even resolving many of these issues, all while achieving increased mobility.

Therefore, the underlying aim of this thesis was to provide a foundation upon which the technology surrounding AET may be further developed by evaluating the operational parameters where AET will be feasible from a transportation operations prospective. The research conducted targeted the subjects of transitioning to an automated electric transportation system as well as quantifying the traffic flow impacts and lane capacity impacts concerning automated freeway lanes and on-ramps, with particular focus placed on the merging strategy at these locations. It also touched on the continuing challenge of modeling automated and/or cooperative vehicle behavior in traffic micro-simulation software packages. As a result, this thesis provides a robust

literature review to understand what has been achieved in past highway/vehicle automation efforts, and identifies areas of improvement.

Central to this research was the formulation of an algorithm that improves upon past automated vehicle entrance logic by updating the limitations of headway spacing with respect to current electric vehicles compared to internal combustion engine vehicles, as well as maximizing mainline and ramp flows under automated control. The expectation is that the work performed in this thesis will provide better understanding of the requirements and potential impacts this technology would have on a typical freeway interchange and provide useful information to transportation professionals attempting to perform analyses in related fields of research.

Conclusion

The information found in this thesis provides quantified measurements in automated lane capacities and traffic flows. The analysis of the algorithm developed was compared to past work that has been done in similar areas. It was shown in this research that the theories and logic presented indeed improve on past successes in terms of ramp capacity and effective capacity of the mainline freeway and was verified using Quadstone Paramics. It was found that by using the logic outlined in this thesis, under the conditions of maximum platoon size set at 5 vehicles per platoon and steady state speeds set at 75 mph, lane capacities may be more than quadrupled to above 8,000 vph for automated vehicle lanes. This is meaningful due to the fact that string stability has been proven for platoon sizes of 5 vehicles, and steady state highway speeds of 75 mph are safely achievable along the majority of today's freeways without alterations to geometric design.

In addition, the strategies utilized in this research maximize automated mainline traffic flow, even at merging areas of the freeways, allowing actual traffic flows to approach maximum

capacity without imposing delay on mainline traffic streams. This information may be useful in cost/benefit analyses for land use and the acquisition of right-of-way.

One major hurdle that was overcome through this research was the lack of existing traffic simulation software packages to be sufficiently flexible to give accurate and reliable estimations of automated traffic flow, especially considering automated vehicle platooning and automated vehicle merging maneuvers at freeway on-ramps. The work presented in this thesis, particularly the algorithm developed, thus has the potential to be integrated with available traffic simulation products such as Paramics (as was used in this research), VISSIM, etc. Improved computer based simulation modeling techniques may prove to be a useful tool to help assess alternative automated entry and exit configurations and further identify optimal strategies to balance traffic management and safety concerns with automated vehicle control.

Recommendations for Future Research

A significant limitation in micro-simulation modeling was that vehicles could not communicate and move simultaneously, or cooperatively. This hurdle was overcome by modifying the car following properties of the vehicles within the software and adjusting the length of the area of analysis in order to allow platoons to form. However, if vehicles had the ability to move cooperatively within the software, many issues in the simulation analysis may be simplified greatly, and the amount of lane miles required for a simple model would be more accurate.

Also, this research introduced an algorithm to overcome past limitations related to automated vehicle entry, but with one key assumption that may be critical to applying the results of this work on the network level. That assumption is that platoons are formed in such a way that the vehicles that will exit from the platoon are always in the rear. However, as destinations for

vehicles arriving at automated vehicle check-in locations will differ stochastically, a strategy for forming platoons optimally remains an area of significant importance.

This optimal platoon configuration may likely be achieved by some strategy at the on-ramps, however, in order to avoid unnecessary delays by forcing vehicles to wait for an optimal mainline platoon structure, it is anticipated that the analysis may have need to expand to include two lanes. The first lane would be designated specifically for steady-state travel, and the second lane would be used for adjusting the platoon structure such that the optimal configuration is achieved by the time the platoon reaches the nearest desired exit of any vehicle in the platoon.

REFERENCES

1. ITS America. Safety Forum Charter. May 21, 2009. <http://www.itsa.org/files/pdf/SafetyForumCharter0509.pdf>. Accessed January 30, 2012.
2. Heaslip, K., K. C. Womack, and J. Muhs. Automated Electric Transportation: A Way to Meet America's Critical Issues. *Leadership and Management in Engineering*, Vol. 11, no. 1, December 2010, pp. 23-28. [http://dx.doi.org/10.1061/\(ASCE\)LM.1943-5630.0000091](http://dx.doi.org/10.1061/(ASCE)LM.1943-5630.0000091).
3. Shladover, S. E. Progressive Deployment Steps Leading Toward an Automated Highway System. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 1727, 2000, pp. 154-161. <http://dx.doi.org/10.3141/1727-19>.
4. Transportation Research Board. *Highway Capacity Manual*, U.S. Customary Version ed. National Research Council, Washington, D.C., 2000.
5. Varaiya, P. Precursor Systems Analysis of Automated Highway Systems Activity Area J Entry/Exit Implementation Final Report. Department of Electrical Engineering and Computer Sciences and PATH, Institute of Transportation Studies, University of California, Berkeley, 1994.
6. Ran, B., S. Leight, and B. Chang. A Microscopic Simulation Model for Merging Control on a Dedicated-Lane Automated Highway System. *Transportation Research Part C: Emerging Technologies*, Vol. 7, no. 6, December 1999, pp. 369-388. http://ac.els-cdn.com/S0968090X99000285/1-s2.0-S0968090X99000285-main.pdf?_tid=8c8a5c52-042f-11e2-ab9b-00000aacb35f&acdnat=1348261484_50f2a03bb5187294ee816626d02ead0f.
7. U.S. Environmental Protection Agency Office of Mobile Sources. Automobile Emissions: An Overview. August 1994. <http://www.epa.gov/otaq/consumer/05-autos.pdf>. Accessed October 4, 2010.
8. Hubbell, B. J., T. Koman, T. J. Fox, N. Possiel, G. Stella, and B. Timin. Health Benefits of Reducing Particulate Air Pollution from Heavy Duty Vehicles. April 21, 2004. <http://www.epa.gov/ttnecas1/workingpapers/hddbten.pdf>. Accessed January 5, 2011.
9. Kurs, A., A. Karalis, R. Moffatt, J.D. Joannopoulos, P. Fisher, and M. Soljacic. Wireless Power Transfer via Strongly Coupled Magnetic Resonances. *Science*, Vol. 317, no. 5834, July 2007, pp. 83-86. <http://dx.doi.org/10.1126/science.1143254>.
10. Divan, D. M., K. W. Klontz, D. W. Novotny, and R. D. Lorenz. Contactless Coaxial Winding Transformer Power Transfer System. 5,314,280, August 23, 1994.

11. Opsahl, K. The Herald Journal. *HJNews.com*, July 6, 2011. http://news.hjnews.com/news/article_46671138-a766-11e0-8e0e-001cc4c03286.html. Accessed February 9, 2012.
12. Yu, X., S. Sandhu, S. Beiker, R. Sassoon, and S. Fan. Wireless energy transfer with the presence of metallic planes. *Applied Physics Letters*, Vol. 99, no. 21, November 2011. <http://dx.doi.org/10.1063/1.3663576>.
13. U.S. Department of Energy. Electric Vehicles. *Energy Efficiency & Renewable Energy*, March 1, 2012. <http://www.fueleconomy.gov/feg/evtech.shtml>. Accessed March 1, 2012.
14. Centers for Disease Control and Prevention. Motor Vehicle Safety. *Injury Prevention & Control*, October 17, 2010. <http://www.cdc.gov/motorvehiclesafety/index.html>. Accessed December 8, 2010.
15. United States Department of Transportation. U.S. Transportation Secretary LaHood Announces Lowest Traffic Fatalities in Six Decades: 2009 Data Show Major Across-the-Board Declines in all Categories Despite a Slight Increase in Road Travel. September 9, 2010. <http://www.dot.gov/affairs/2010/dot16510.html>. Accessed October 4, 2010.
16. Sheridan, T. B. Risk, Human Error, and System Resilience: Fundamental Ideas. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, Vol. 50, no. 3, June 2008, pp. 418-426. <http://dx.doi.org/10.1518/001872008X250773>.
17. National Highway Traffic Safety Administration. Highlights of 2009 Motor Vehicle Crashes. *Traffic Safety Facts*, August 2010. <http://www-nrd.nhtsa.dot.gov/Pubs/811363.pdf>. Accessed December 9, 2010.
18. U.S. Census Bureau. (1952) Number of Inhabitants: United States Summary. <http://www2.census.gov/prod2/decennial/documents/23761117v1ch03.pdf>.
19. U.S. Census Bureau. U.S. & World Population Clocks. *U.S. Census Bureau: Population Division*, August 25, 2010. <http://www.census.gov/main/www/popclock.html>. Accessed December 8, 2010.
20. Reason, J. *Human Error*. Cambridge University Press, Cambridge, United Kingdom. <http://books.google.com/books?id=WJL8NZc8lZ8C&pg=PA9&lpg=PA9&dq=a+generic+term+to+encompass+all+those+occasions+in+which+a+planned+sequence+of+mental+or+physical+activities+fails+to+achieve+its+intended+outcome,+and+when+these+failures+cannot+be+attribute>, 1990.
21. Salmon, P. M., M. G. Lenne, N. A. Stanton, D. P. Jenkins, and G. H. Walker. Managing error on the open road: The contribution of human error models and methods. *Safety*

- Science*, Vol. 48, no. 10, December 2010, pp. 1225-1235. <http://dx.doi.org/10.1016/j.ssci.2010.04.004>.
22. Koppa, R. J. Human Factors. In *Revised Monograph on Traffic Flow Theory*, ch. 3, 1992. <http://www.fhwa.dot.gov/publications/research/operations/tft/chap3.pdf>.
 23. Rothery, R. W. Car Following Models. In *Revised Monograph on Traffic Flow Theory*, ch. 4, 1992. <http://www.fhwa.dot.gov/publications/research/operations/tft/>.
 24. Pipes, L. A. An Operational Analysis of Traffic Dynamics. *Journal of Applied Physics*, Vol. 24, no. 3, 1953, pp. 274-281.
 25. May, A. D. *Traffic Flow Fundamentals*. Prentice Hall, Englewood Cliffs, N. J., 1990.
 26. Aycin, M. F., and R. F. Benekohal. Comparison of Car-Following Models for Simulation. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 1678, 1999, pp. 116-127.
 27. Brackstone, M., and M. McDonald. Car-Following: A Historical Review. *Transportation Research Part F: Traffic Psychology and Behaviour*, Vol. 2, no. 4, December 1999, pp. 181-196.
 28. Federal Highway Administration. *Highway Capacity Manual*. U.S. Government Printing Office, Washington, D.C., 1950.
 29. Garber, N. J., and L. A. Hoel. *Traffic & Highway Engineering*, 4th ed. Cengage Learning, Toronto, Ontario, Canada, 2009.
 30. Spyropoulou, I. Simulation Using Gipps' Car-Following Model - An In-Depth Analysis. *Transportmetrica*, Vol. 3, no. 3, June 2007, pp. 231-245. <http://www.tandfonline.com/doi/pdf/10.1080/18128600708685675>.
 31. Encyclopedia Britannica Inc. Automobile. *Britannica Academic Edition*, 2012. <http://www.britannica.com/EBchecked/topic/44957/automobile/64377/History-of-the-automobile>. Accessed March 3, 2012.
 32. General Motors Corporation. 1939/40 New York World's Fair (Futurama I). *GM Drive to 2030*, August 23, 2009. <http://www.gmexpo2010.com/en/history/193940-new-york-worlds-fair-futurama-i>. Accessed March 3, 2012.
 33. Transportation Research Board. National Automated Highway System Research Program, in *Special Report 253: National Automated Highway System Research Program - A Review*.

- Washington, D.C., United States of America: National Academy Press, ch. 4, 1998, pp. 40-62. <http://onlinepubs.trb.org/onlinepubs/sr/sr253/sr253fm.pdf>.
34. Tsao, J. H.-S., L. Zhang, L. Lin, and D. Batni. Task Order 4236 Final Report - Evaluation of Bus and Truck Automation Operations Concepts. Department of Industrial and Systems Engineering, San Jose State University, Research Report 1055-1425, 2004.
 35. Shladover, S. E., X.-Y. Lu, B. Song, S. Dickey, C. Nowakowski, A. Howell, F. Bu, D. Marco, H.-S. Tan, and D. Nelson. Demonstration of Automated Heavy-Duty Vehicles. University of California, Berkeley, Research Report 1055-1425, 2005.
 36. National Automated Highway System Consortium. Automated Highway System (AHS) - Milestone 2 Report. 1997.
 37. Goldbeck, J., B. Huertgen, S. Ernst, and L. Kelch. Lane Following Combining Vision and DGPS. *Image and Vision Computing*, Vol. 18, no. 5, April 2000, pp. 425-433. [http://dx.doi.org/10.1016/S0262-8856\(99\)00037-2](http://dx.doi.org/10.1016/S0262-8856(99)00037-2).
 38. American Association of State Highway and Transportation Officials. *A Policy On Geometric Design of Highways and Streets*, 5th ed. Washington, D.C., 2004.
 39. Kou, C.-C., and R. B. Machemehl. Modeling Vehicle Acceleration-Deceleration Behaviour During Merge Maneuvers. *Canadian Journal of Civil Engineering*, Vol. 24, no. 3, 1997, pp. 350-358.
 40. Polus, A., M. Livneh, and J. Factor. Vehicle Flow Characteristics on Acceleration Lanes. *Journal of Transportation Engineering*, Vol. 111, no. 6, November 1985, pp. 595-606.
 41. Bishop, J. R., and W. Stevens. Precursor Systems Analyses of an Automated Highway System. in *Vehicular Technology Conference, 1993 IEEE 43rd*, Secaucus, NJ, USA, 1993, pp. 364-367. <http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=507487>.
 42. Hall, R. W., A. Nowroozi, and J. Tsao. Entrance Capacity of an Automated Highway System. *Transportation Science*, Vol. 35, no. 1, February 2001, pp. 19-36. <http://web.ebscohost.com/ehost/pdfviewer/pdfviewer?sid=b379ad36-3b5b-4a6e-a6dd-e1ac917d8d47%40sessionmgr12&vid=2&hid=7>.
 43. Weingroff, R. F. Federal-Aid Highway Act of 1956: Creating the Interstate System. *Public Roads*, Vol. 60, no. 1, 1996. <http://www.fhwa.dot.gov/publications/publicroads/96summer/p96su10.cfm>.

44. Pfeiffer, D. A. Ike's Interstates at 50 Anniversary of the Highway System Recalls Eisenhower's Role as Catalyst. *Prologue*, Vol. 38, no. 2, 2006. <http://www.archives.gov/publications/prologue/2006/summer/interstates.html>.
45. Emadi, A., Y. J. Lee, and K. Rajashekara. Power Electronics and Motor Drives in Electric, Hybrid Electric, and Plug-In Hybrid Electric Vehicles. *IEEE Transactions on Industrial Electronics*, Vol. 55, no. 6, June 2008, pp. 2237-2245. <http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=4493430&tag=1>.
46. Salt Lake City Transportation Division. (2007, December) Does My Vehicle Qualify as a SLC "Green Vehicle"? Brochure. http://www.slcclassic.com/transportation/Parking/pdf/FMP_Brochure12_06_07a.pdf.
47. Cikanek, S. R., and K. E. Bailey. Regenerative Braking System for a Hybrid Electric Vehicle. in *American Control Conference*, Vol. 4, Anchorage, 2002, pp. 3129-3134. <http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=1025270>.
48. Foy, P. Utah to Deploy Electric Bus that Needs No Plug. *Tech & Science - Innovation*, November 25, 2011. http://www.msnbc.msn.com/id/45438112/ns/technology_and_science-innovation/t/utah-deploy-electric-bus-needs-no-plug/#.TzmtX5hQa-E. Accessed March 20, 2012.
49. Virginia Department of Transportation. High Occupancy Vehicle (HOV) Lanes - Rules and FAQs. *Travel Center*, January 23, 2012. <http://www.virginiadot.org/travel/hov-rulesfaq.asp>. Accessed March 20, 2012.
50. Varaiya, P. What We've Learned About Highway Congestion. *Access*, Vol. 27, 2005, pp. 2-9. http://robotics.eecs.berkeley.edu/~varaiya/papers_ps_dir/accessF05v2.pdf.
51. Fenton, R. E. Automatic Vehicle Guidance and Control - A State of the Art Survey. *IEEE Transactions on Vehicular Technology*, Vol. 19, no. 1, February 1970, pp. 153-161. <http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=1621995>.
52. Liu, Y., and Z. Wu. A Smart Car Control Model for Driver's Comfort of Car Following. in *Intelligent Vehicles Symposium*, 2005, pp. 833-839. <http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=1505208&isnumber=32246>.
53. Li, P., L. Alvarez, and R. Horowitz. AHS Safe Control Laws for Platoon Leaders. *IEEE Transactions on Control Systems Technology*, Vol. 5, no. 6, November 1997, pp. 614-628. http://www.me.berkeley.edu/~horowitz/Publications_files/Papers_numbered/Journal/27j_Li_AVHS_safe_control_IEEE_TCST97.pdf.

54. Shladover, S. E. Dynamic Entrainment of Automated Guideway Transit Vehicles. *High Speed Ground Transportation Journal*, Vol. 12, no. 3, 1978, pp. 87-113.
55. Shladover, S. E. Operation of Automated Guideway Transit Vehicles in Dynamically Reconfigured Trains and Platoons (Extended Summary). Massachusetts Institute of Technology and Urban Mass Transportation Administration, UMTA-MA-06-0085-79-1Final Rpt., 1979.
56. Tsao, H.-S. J., R. W. Hall, and S. E. Shladover. Design Options for Operating Automated Highway Systems. in *Vehicle Navigation and Information Systems Conference, 1993., Proceedings of the IEEE-IEE*, 1993, pp. 494-500. <http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=585680&isnumber=12662>.
57. Fernandes, P., and U. Nunes. Platooning of Autonomous Vehicles with Intervehicle Communications in SUMO Traffic Simulator. In *13th International IEEE Conference on Intelligent Transportation Systems (ITSC)*, Funchal, Madeira Island, Portugal, 2010, pp. 1313-1318. <http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5625277&isnumber=5624963>.
58. Fernandes, P., and U. Nunes. Platooning with IVC-Enabled Autonomous Vehicles: Strategies to Mitigate Communication Delays, Improve Safety and Traffic Flow. *IEEE Transactions on Intelligent Transportation Systems*, Vol. 13, no. 1, March 2012, pp. 91-106. <http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6135795&isnumber=6157683>.
59. Liu, J.-C., J. L. Kim, Y. Chen, Y. Hao, S. Lee, T. Kim, and M. Thomadakis. An Advanced Real-Time Ramp Metering System (ARMS): The System Concept. Texas Transportation Institute, Research Report 1232-24 November 1994. http://alphamike.tamu.edu/web_home/papers/TR-123224.pdf.
60. McCasland, W. R. Freeway Ramp Control System. Texas Transportation Institute, Research Report 24-26 1969. <http://tti.tamu.edu/documents/24-26F.pdf>.
61. Peters, A. A., and R. H. Middleton. Leader Velocity Tracking and String Stability in Homogeneous Vehicle Formations with a Constant Spacing Policy. In *9th IEEE International Conference on Control and Automation*, Santiago, 2011, pp. 42-46. <http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6138068&isnumber=6137867>.
62. Seiler, P., A. Pant, and K. Hedrick. Disturbance Propagation in Vehicle Strings. *IEEE Transactions on Automatic Control*, Vol. 49, no. 10, October 2004, pp. 1835-1842. <http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=1341587&isnumber=29559>.

APPENDIX

APPENDIX
VISUAL BASIC COMPUTER CODE

'Define Variables

Public l As Integer ' Vehicle Length, [m]

Public u As Integer ' Average Speed, [km/h]

Public h As Integer ' Intra-Platoon Headway, [m]

Public Hsafe As Integer ' Inter-Platoon Headway, [m]

Public Nmax As Integer ' Maximum Platoon Size, [veh]

Public nDemand As Integer ' Ramp Demand, [veh]

Public Np As Integer ' Size of the Platoon Preceding the Gap, [veh]

Public G As Integer ' Gap Size, [m]

Public Q As Integer ' Mainline Flow, [veh/hr]

Public i As Integer ' Counter for the Number of Platoons Analyzed for the Existing Gap,
[platoons]

Public n As Integer ' Counter for the Number of Vehicles, [veh]

Public nEnter As Integer ' Number of Vehicles that can Fit into a Gap, [veh]

Public nTotal As Integer ' Total Number of Vehicles that are Released for the Existing Gap, [veh]

Public nJoin As Integer ' Number of Vehicles that Join the Rear of the Platoon Preceding the Gap,
[veh]

Public nFull As Integer ' Number of Full Platoons that are Released in the Existing Gap,
Excluding the Platoon Preceding the Gap and the Last Platoon Analyzed, [veh]

Public nLast As Integer ' Number of Vehicles that are Released in the Last Platoon Analyzed,
Excluding the Platoon Preceding the Gap, [veh]

Public Cleak As Integer ' Capacity Leak, or Excess Headway Existing After the Analysis, [m]

Public qRamp As Integer ' Ramp Flow, [veh/hr]

Function AETEntry(Nmax, Np, Q)

'Input Given Data

l = Range("D3").Value

u = Range("D4").Value

h = Range("D5").Value

Hsafe = Range("D6").Value

nDemand = Range("D8").Value

'Initial Conditions

i = 1

nTotal = 0

G = Application.WorksheetFunction.RoundDown(((3600 * Np) / Q) * (u * (1000 / 3600)) -
Np * (l + h) + h, 0)

'Block 1

nEnter = Application.WorksheetFunction.RoundDown((G - Hsafe) / (l + h), 0)

'Diamond 2

If nEnter > Nmax - Np Then

'Diamond 3

If Nmax - Np > nDemand Then

'Block 4

n = nDemand

Else

'Block 5

n = Nmax - Np

```
End If
Else
'Diamond 6
If nEnter > nDemand Then
    'Block 4
    n = nDemand
Else
    'Block 7
    n = nEnter
End If
End If
'Block 8
nJoin = n
nDemand = nDemand - n
nTotal = n
G = G - n * (1 + h)
'Diamond 9
While G >= 2 * Hsafe + 1 And nDemand > 0
    'Block 10
    nEnter = Application.WorksheetFunction.RoundDown((G - 2 * Hsafe + h) / (1 + h), 0)
'Diamond 11
If nEnter > Nmax Then
    'Diamond 12
    If Nmax > nDemand Then
        'Block 13
```

```
        n = nDemand
    Else
        'Block 14
        n = Nmax
    End If
Else
    'Diamond 15
    If nEnter > nDemand Then
        'Block 13
        n = nDemand
    Else
        'Block 16
        n = nEnter
    End If
End If
'Block 17
G = G - Hsafe - n * (l + h) + h
nLast = n
nDemand = nDemand - n
nTotal = nTotal + n
i = i + 1
Wend
'End (Diamond 18)
If i < 3 Then
    'Block 19
```

```
nFull = 0  
Else  
    'Block 20  
    nFull = i - 2  
End If  
'Block 21  
    Cleak = G - Hsafe  
'Block 22: Output  
'Return to Start  
    qRamp = nTotal * (Q / Np)  
    AETEntry = qRamp  
End Function
```