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AN INTEGRATED DECISION-MAKING METHOD TO IDENTIFY DESIGN REQUIREMENTS THROUGH AGENT-BASED SIMULATION FOR PERSONAL AIR VEHICLE SYSTEM

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Abstract

A product's design requirements guide the next development efforts. Thus, correct decision-making is critical in generating design requirements as vehicle concepts are being formulated. A new method is proposed to account for system-of-systems aspects and to aid a decision-making process in synthesizing design requirements for a personal air vehicle system. The use of an agent-based modeling technique facilitates the abstraction of the key elements in the whole system. A traveling party is treated as an agent, and the infrastructure environment in the national transportation system is easily represented in the model. A number of simulations are performed to demonstrate the capability of this new approach. The method not only measures the effect of design requirements of a personal air vehicle system through sensitivity analyses, but also evaluates the effect of system technologies quantitatively, while maintaining the system-of-systems perspective. With this powerful method, designers can extract essential technical requirements that allow polishing of concept vehicles; policy makers can investigate the infrastructure and technology impact of new systems; and business planners can perform an analysis based on their own market assumptions.

Acronyms

PAV(s)	Personal Air Vehicle(s)
NTS	National Transportation System
ABM	Agent-Based Model(ing)
ABM/S	Agent-Based Modeling/Simulation
CTOL	Conventional Takeoff and Landing
VTOL	Vertical Takeoff and Landing

Introduction

If a complex system is under pressure to improve and evolutionary improvements to existing products in a system are not sufficient to achieve the desired level of improvement, a new product has to be developed and introduced into the existing system. A personal air vehicle (PAV), conceivably revolutionizing our daily life in the future, is such an example. Aerospace engineers have come up with numerous concept vehicles since the first flight was proclaimed by the Wright brothers.[1, 2] Nevertheless, the general public has not embraced any of them because current PAV technologies have not reached a readiness level commensurate with various constraints such as performance, cost or environmental compatibility.

Certainly, the lack of mature technologies is a barrier and thus, the research and development community needs to continue to seek innovations. However, how are they to be guided in this process? The present paper does not address a vehicle-specific or technology-oriented topic. Rather, it intends to look at the larger problem of requirements exploration that must precede the detailed design phases. The discussion begins by considering the generic product design and development process shown in Figure 1.

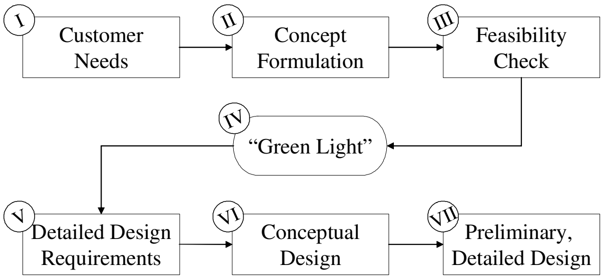

Figure 1: Design and Development Process

Until now, the dream of PAV has met a bottleneck at step III. Radical concepts proposed concepts by enthusiasts have skipped the step III and IV and gone directly to step V. On the other hand, NASA has recognized that the PAV design space is huge and ill-defined. NASA's

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PAV project in the Revolutionary Aerospace Systems Concepts (RASC) Program has laid the foundation for examination of emerging concepts in the context of the requirements space.[3] This paper describes one method that assists in this aspect by exploring the decision of when to give the "green light".

From the above line of reasoning, it may be good to have a method to evaluate a concept vehicle in step II. The question, then, concerns evaluation of various PAV concepts. Instead of looking from a detailed vehicle design/analysis viewpoint, understanding the leverage effect of a vehicle's top level design requirements may be another means to answer the question. This task is important before firm requirements are mandated. Also, it must be recognized that PAV differs from other aerospace products, such as Joint Strike Fighter, in that it eventually should appeal to a significant percentage of the general public. This leads to considering the market and its dynamic behavior in synthesizing design requirements. Vehicle-oriented or technology-driven design processes often ignore this aspect.

A number of existing approaches already exist within the aerospace tradition to address parts of this challenge. Many have used expert opinions. Experts may have a lengthy off-line meeting and finally come up with a guideline concerning design requirements with authoritative expertise. Systems engineering has a set of tools to guide experts. Quality Function Deployment (QFD) is such a tool designed to elicit and rank customer needs in understanding system requirements.[4] However, it is limited to generating qualitative assessments and has low fidelity in real cases.

Some inroads have been made at requirements synthesis for more evolutionary systems by creative reuse of vehicle synthesis tools. This approach, called the Unified Trade-off Environment, offers a framework to analyze design requirements, design and economic variables, and potential technologies simultaneously.[5] This method is primarily suited for a well-defined conceptual design problem and is not applicable for a revolutionary design. Also, the method is incapable of dealing with the dynamic behavior of the customers.

In other fields, the generation of new requirements is also handled in a formal manner. There is a research thrust called requirement engineering in the electrical and electronics engineering fields.[6] It has been positioned as a key activity in the development of software systems. The design philosophy and product development procedures in these fields are different from those of aerospace engineering, so it may be difficult to adopt requirement engineering to the aerospace area in practical ways.

Within the context of the review above, a new approach is needed to account for the system-of-systems aspect and to aid the decision-making process in synthesizing PAV design requirements. This research proposes an integrated decision-making method to identify PAV design requirements in the concept formulation step. The method utilizes an agent-based modeling and simulation (ABM/S) technique that make it possible to easily maintain the system-of-systems standpoint. The first step is to model the whole system, in this case, the national transportation system (NTS). Then a PAV system is inserted into the model.

Method

Analysis of the NTS

The study begins with a sound conceptual understanding of the NTS where countless elements reside. In Figure 2, the hierarchy of the NTS is shown.

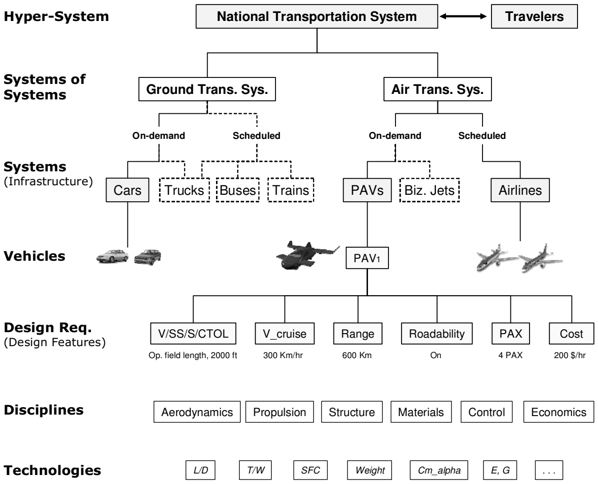


Figure 2: Hierarchy of National Transportation System

The NTS on top, which interacts with travelers, can be divided into a ground transportation system and an air transportation system according to the primary mission space. The air transportation system has multiple systems. Airlines and business jets (general aviation) are listed as elements of the air transportation system. Airlines consist of multiple service providers, vehicles, and infrastructure. General aviation utilizes a somewhat different infrastructure, with smaller airports and low-altitude air routes. The hypothetical PAV system envisioned in the figure has a particular set of design requirements. In fact, any PAV concept can be abstracted through this breakdown.

Travelers are adaptive entities with respect to any changes in the NTS. If one of the features of the PAV is altered, a traveler's knowledge about the PAV is updated and the same traveler can then choose a different vehicle. That is, a change in PAV design requirements at the very bottom level or a change in market conditions will propagate all the way up to the top level, the NTS. Travelers will interact with a new different NTS. This mechanism involves complicated dynamic processes that cannot be completely understood or easily modeled.

If PAV design requirements are determined from an NTS analysis, engineers from various disciplinary areas can cooperate with one another to come up with a viable design while improving technologies within specific disciplinary circles. This can be called an "engineering" problem in a traditional sense. However, as of today, knowledge about PAV design requirements is at issue. We need to attack a "decision-making" problem first.

Agent-Based Modeling of the NTS

Modeling the NTS, the real world, is a challenging task. It is next to impossible to model all the airports, highways and geographic conditions in the nation even though they all have well-defined physical characteristics. Furthermore, it is impossible to represent numerous travelers passing through the nation everyday. The NTS cannot be described in a mathematical model with governing equations and boundary conditions. It may be possible to adopt an approach from system dynamics utilizing stocks and flows analysis, and causal loop diagram,[7] but one may soon encounter very complicated structure.

As a possible solution to this, an agent-based modeling and simulation (ABM/S) technique was introduced. An agent is defined as an entity that fits autonomously in a certain environment.[8] An agent sees the world, and then it makes a decision that entails an action. The world is influenced by the action, even by the smallest bit. The same agent now sees a different world, and then it updates its knowledge, which may cause a different action. This mechanism is portrayed in Figure 3.

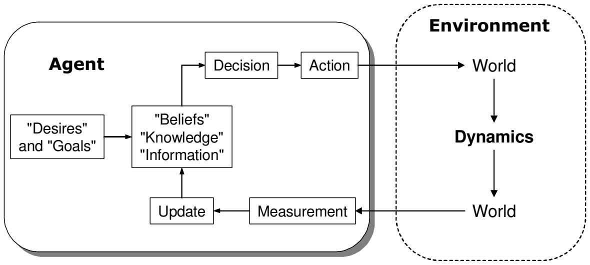


Figure 3: Agent and Environment

ABM/S is another scientific reasoning in addition to deduction and induction.[9] After rules for guiding an agent's actions and a number of relationships between the agent and environment are established, a model that imitates the real world is simulated on a computer. The observation and analysis should follow the simulation invoked by a user: *let them play and watch it*. A collective action of agents produces an "emergent behavior", which often renders a useful insight to the real world even if a model itself is in a very simple form. The major strength of ABM/S comes from the fact that it is a simple, versatile and flexible method that is well suited for studies of complex nonlinear systems. However, it has its downside. For a highly realistic model, large amounts of data input and computation may be needed. Another issue that plagues ABM/S is that identifying the "right" rules or behaviors that capture the real dynamics can be somewhat ad hoc in nature.[10]

The modeling in the present work utilizes the features of ABM that make it possible to abstract and simplify the representations of key elements in the NTS with less effort. The following section outlines the modeling details.

Agents: Travelers

Members of the traveling public were treated as "agents" in the beginning of the modeling work. Travelers' goals are to complete their round trips safely, with less travel time and money spent. In the present model, a unit agent indicates one travel party; an agent can be a business traveler flying on a moment's notice or a four-person family visiting grandparents on a long-planned vacation. The various features that make the traveling public diverse are shown in Figure 4. The differences in these characteristics behind the individual travelers drive them towards specific transportation options.

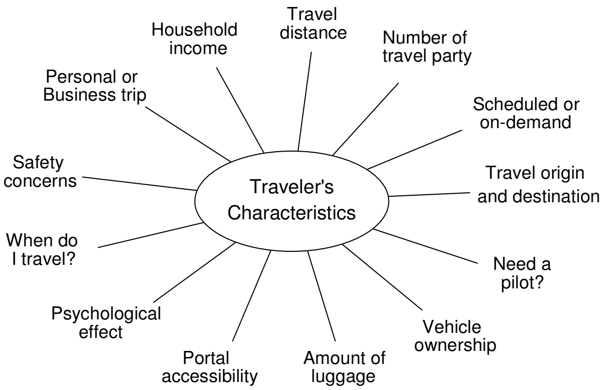


Figure 4: Traveler's Profile

Among these characteristics, some were available from published government data.[11 – 14] Others were tailored by the authors. In Figures 5 and 6, the sample input distributions of annual household income and travel distance, considered as the most important factors, are depicted.

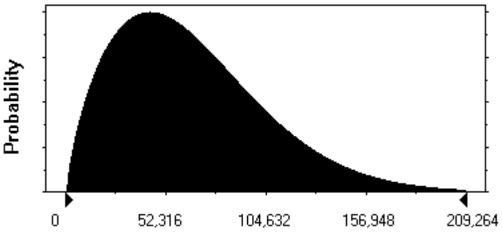


Figure 5: Household Income Distribution (in USD)

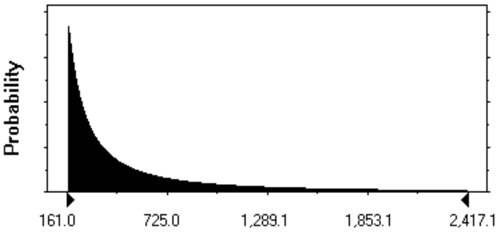


Figure 6: Travel Distance Distribution (in km)

Descriptions of all the necessary data, mostly as probability distribution functions, were prepared before the Monte Carlo simulation technique was employed to make all agents heterogeneous. The resultant set of agents can be considered as representative of the traveling public in the nation over a year. The number of agents used was about 50,000 for a single year simulation. Only long-distance travel (over 100 miles in one-way trip distance) was considered because there were no data available about short-distance trips from the sources at hand. The action of an agent is to choose from available travel options. This choice mechanism is shown through the following procedure, which is not absolute but is enough to explain the general behavior of an agent.

1. Compute total trip time T_k (hours) and perceived cost P_k (chained 2000 U.S. Dollars) for each vehicle k
2. Calculate selection cost S_k for each vehicle k from the following equation:

$$S_k = w_1\left(\frac{D}{2000}\right)\cdot T_k + w_2 P_k \qquad (1)$$

3. Select vehicle k such that minimize S_k

In Equation (1), the two weight coefficients w_1 and w_2 were subject to probabilistic distribution functions to offer the representations of somewhat fuzzy and erratic personal inclinations. The number in the denominator just indicates approximate working hours during a year, and D represents household income for an agent with the same unit as P_k. The detailed description of T_k and P_k appears in the next subsection.

Environment: Vehicles and Infrastructures

Characteristics of transportation vehicles, the infrastructures and various other factors that affect trips are integrated as part of the environment with which the agents interact. The statistical data indicates that personal autos and commercial transports cover the majority (about 97%, see Figure 8a) of long-distance travels in the U.S. Thus, the effects of secondary modes of transport, such as business jets, trains and buses, were assumed to be negligible. However, these options can be easily added in the model if needed be. An agent passes through intermediate stops or portals to complete a door-to-door trip. For a car system, highway ramps and exits are departure and arrival portals. For commercial air transport, the distance from a departure base to a departure portal – it can be a local airport or hub airport depending on the location of an agent – may be longer than that of cars in general. The mental model for each vehicle's route is shown in Figure 7.

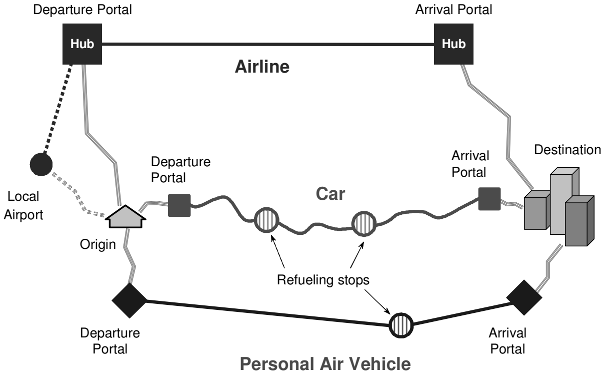


Figure 7: Door-to-Door Travel Routes

For any given agent, T_k and P_k can be obtained for each vehicle k. The most important point in the modeling of the calculation block for each vehicle was to provide an agent with rational information on total trip time and perceived cost.

For commercial air transport, ticket price and flight time can be described as a function of travel distance by regression analysis on actual data. On the top of that, extra money and time can be considered as part of finishing the trip – standby or waiting time at portals should be included in total trip time. In addition, transit cost and time are needed, for example, to move an agent from arrival portal to final destination.

The time and cost for a car trip, T_{car} and P_{car}, can be computed in a similar manner, but waiting time at a portal is negligible. Cruise speed on the highway is 120 km/h with a small variability. The gasoline price assumed is \$1.50/gallon. Path length factor, which makes ground travel distance longer than the linear distance between points, is 1.25 with a small variability as well.

Since a PAV is not part of the existing transportation system, it is not so easy to calculate T_{pav} and P_{pav}. Trip time may be easier. It is also a function of design requirements, such as cruise speed and accessibility to a portal. The cost model for a PAV is especially problematic because no working business model exists. The first strategy to help this situation is to assume that a PAV system operates like rental car business, although the model can implement different cost models such as air-taxi or partial ownership. This rent-a-PAV assumption may not be absurd since a PAV system will need an intermediate phase before entering the era of massive operations by the public. The cost is calculated by multiplying a unit price in terms of \$/hour and number of flight hours. Originally, numeric values for a unit price depend on specific design requirements. However, in the simulation, the cost value is treated as an independent variable; a user arbitrarily sets it in simulating a specific scenario. This is a key strategy for calculating P_{pav}, which enables in comparing different concept vehicles. Other important assumptions related to PAV systems were brought by NASA's Small Aircraft Transportation System (SATS) Program. For example, the easy-to-fly and the distributed air traffic control technology are assumed to have reached a mature level from 2010, thanks to the successful completion of the SATS program. So, the traveling public in the virtual world can enjoy on-demand PAV travel while using over 5,000 currently underutilized public airports throughout the nation. A computer code, named **Mi**[15], was developed to incorporate the elements in the NTS discussed above to prepare the actual simulation.

Simulation

Agent-based modeling should accompany a simulation that is driven by a scenario. A scenario is a unit situation with a particular PAV that has a set of design requirements. To this end, top-level design requirements are decomposed and the corresponding settings are itemized, shown in Table 1.

Table 1: Summary of PAV Design Requirements

Requirements	Settings		
Nominal cruise speed (km/hr)	300	**350**	400
Number of passenger seats	2	**4**	6
Refueling range (km)	600	**900**	1200
Easy-to-fly technology	**ON**		OFF
Roadability	ON		**OFF**
Takeoff and Landing	**CTOL**		VTOL

A combination of these settings puts together a hypothetical PAV system. Any vehicles can be made without difficulty regardless of vehicle platform (fixed wing aircraft, helicopter or even autogiro with appropriate assumptions) using this strategy. The settings of the baseline PAV, which is a basis for sensitivity analyses, are indicated by the **bold** type in the table.

Now imagine the NTS with a particular PAV. Once a specific PAV system is determined, a set of agents is generated with given probability distribution functions that account for various characteristics of agents. Each agent selects its best transportation method, and the choice vehicle is recorded. As explained, PAV cost is varied by a user. Then, the Monte Carlo simulations are repeated with different PAV cost values. The simulation for the PAV scenario is then completed.

The model was calibrated before the main simulations. The simulation initialization from a base year of 1995 to 2000 was tuned to match available historical data. This is called Scenario A_0. Scenario A_1 is the next logical step. It projects growth and utilization numbers from 2001 until 2010. This scenario was necessary to accommodate the SATS vision – as ordinary people begin to fly by themselves from 2010. One major assumption was introduced in Scenario A_1. Due to the September 11 incident, travel demand in the year 2001 was assumed to go back to that of 1997, with similar growth to that of before the tragedy. These two scenarios, A_0 and A_1, were preparatory steps for the final baseline scenario. In Scenario B, the baseline PAV was inserted into the virtual world. The baseline scenario laid a foundation for sensitivity analyses. For example, Scenario V_H, described in Table 2, examined an impact on the NTS by increasing the nominal cruise speed of the baseline PAV to 400 km/hr, keeping the other design requirements the same. This one-variable-at-a-time strategy was a basic way to understand the leverage effect on the NTS. Descriptions of all scenarios examined are summarized in Table 2.

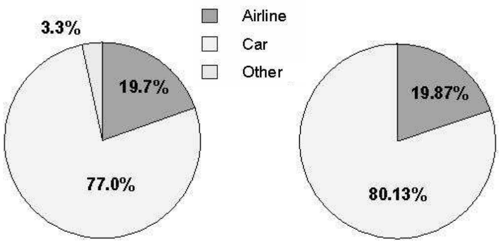
Table 2: Simulation Scenarios

Code	Vehicle Description
A_0	1995 thru 2000, without the baseline PAV
A_1	2001 thru 2010, without the baseline PAV
B	Introduce the baseline PAV in 2010
V_L	Cruise speed = 300 km/hr
V_H	Cruise speed = 400 km/hr
P_2	Two-passenger seats (including a pilot's)
P_6	Six-passenger seats (including a pilot's)
R_L	Refueling range = 600 km
R_H	Refueling range = 1,200 km
C	Easy-to-fly technology turned off
D	Roadability added to the baseline PAV

Results and Discussion

Baseline Scenarios

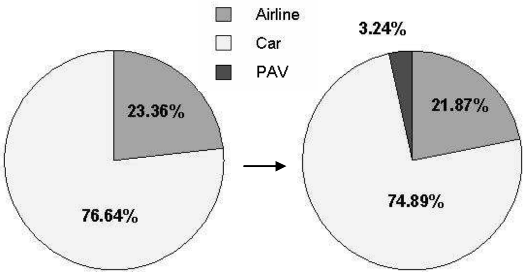
Scenario A_0 was the historical baseline. The purpose of this scenario was to calibrate the model. The result for 1995 is shown in Figure 8b. Airlines occupied 19.87% of all household trips.



a. Published Data[10] b. Scenario A_0 Result

Figure 8: Calibration Result– choice vehicle (year 1995)

Scenario A_1 followed. It projected growth and utilization numbers until 2010, taking into account the drop in travel volume after September 11. The result of Scenario A_1, without a PAV yet in the market, shows that the airline market share increases by 3.5% as plotted in Figure 9a. Now that the Scenario A_1 has been established, the baseline PAV was introduced in 2010. Scenario B had five cases, since PAV cost was implemented as an independent variable. Figure 9b shows the result of the case with PAV price of $150/hr. In this case, the baseline PAV system attracted 3.24% of all household trips, 1.49% and 1.75% from airline and car travelers respectively.



a. Scenario A_1 Result b. Scenario B Result

Figure 9: Prediction Result – choice vehicle (year 2010)

Four independent Monte Carlo simulations were repeated with PAV prices of $120/hr, $100/hr, $80/hr and $60/hr. Results from the five cases were analyzed as in Figure 9b. The variation of the three vehicles' market share is summarized in Figure 10. More travelers chose a PAV, including those who initially selected a different travel option, as the PAV price became cheaper.

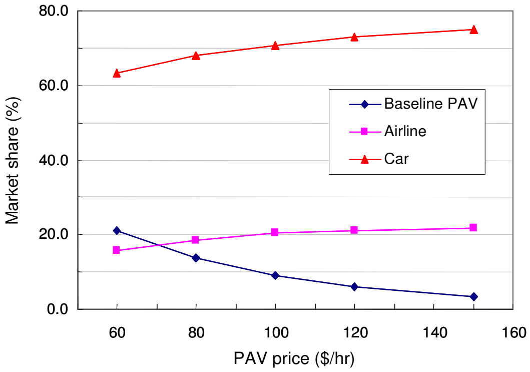


Figure 10: Vehicles' market shares

In Figure 11, the PAV data from Figure 10 is plotted on a Log scale. The figure reveals information that is not immediately obvious. Regression analysis shows that a practically perfect exponential relationship exists. Similar trends were found throughout all simulation scenarios. This can be considered as one of the "emergent behaviors" in the present ABM.

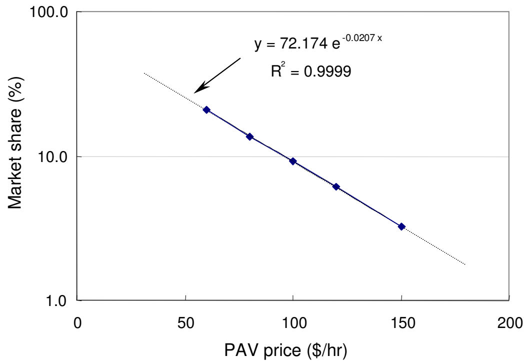


Figure 11: Baseline PAV's Market Share

Further analysis follows from a different angle. The distribution of agents' vehicle choice over household income and travel distance can be visualized in a 'market space' plot. Figures 12 and 13 had upper bounds of 4,400 km for the X-axis, the approximate distance from Seattle to Miami. Then they were zoomed in for a close investigation. Each mark represents a unit agent – a single travel party of between 1 and 6 people. An agent's choice is indicated by a small dot (car), cross (airline) or circle (baseline PAV). In the first plot with PAV price of $150/hr, the majority of people using the baseline PAV are quite wealthy and flying more than 350 km. As PAV price drops to $100/hr, the market region expands into lower income and short-distance travelers as portrayed in Figure 13. From these powerful plots, a decision-maker quickly monitors the changes in the potential PAV market region visually and dynamically.

X-axis: distance in km, Y-axis: annual household income in USD

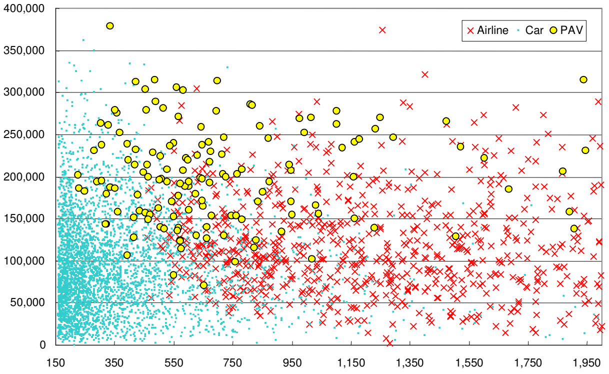


Figure 12: Market Space Plot of Scenario B ($150/hr)

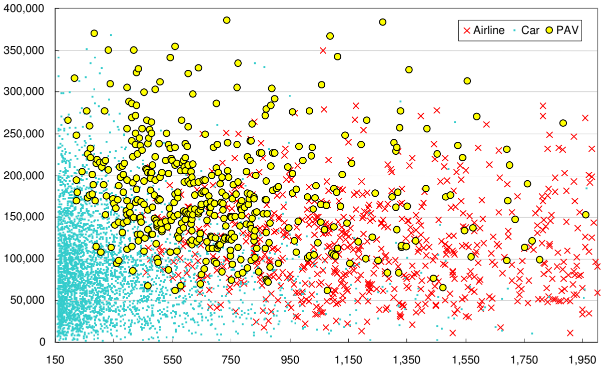


Figure 13: Market Space of Scenario B ($100/hr)

Sensitivity Analysis of Design Requirements

A series of charts that showcase of the leverage effects on the NTS due to changes in design requirements from the baseline PAV follows. Through Scenarios V_L and V_H, the sensitivity analysis of the PAV market share to nominal cruise speed was carried out. Obviously, increasing airspeed gave a benefit as verified in Figure 14. The beauty of this figure is to convey the benefit quantitatively.

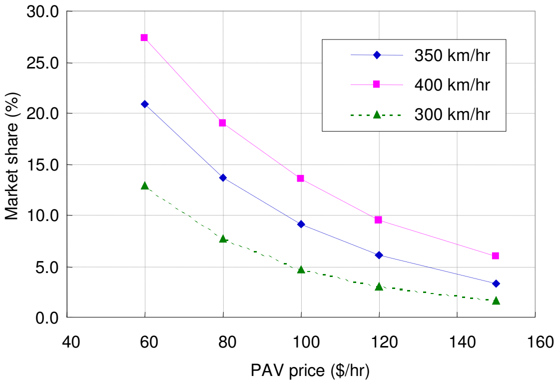


Figure 14: Result of Scenario V_L and V_H

The next scenarios, P_2 and P_6, examined the effect of varying PAV passenger capacity. If other conditions are kept the same, big aircraft incur expensive acquisition cost. This is not always a bad situation because travel cost per capita can be reduced if a vehicle operates at a full load. The simulation showed that a decrease in passenger capacity from the baseline of four to two resulted in a significant decrease in market share. However, an increase in passenger capacity to six did not yield as great a change, shown in Figure 15. This is in line with the initial assumption that specified relatively small travel parties.

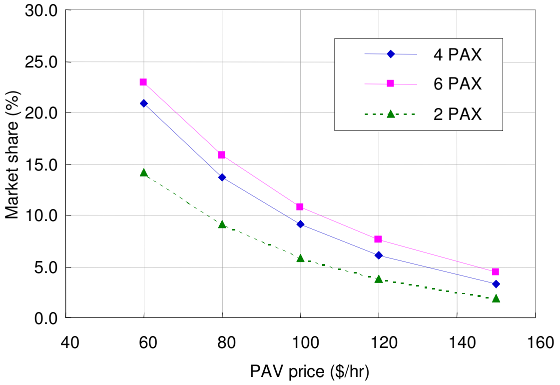


Figure 15: Result of Scenario P_2 and P_6

Scenarios R_L and R_H were intended to gauge the sensitivity to the changes in refueling range. In Figure 16, increasing refueling range by 300 km does not have much benefit, while decreasing range by 300 km results in missing a salient amount of travelers.

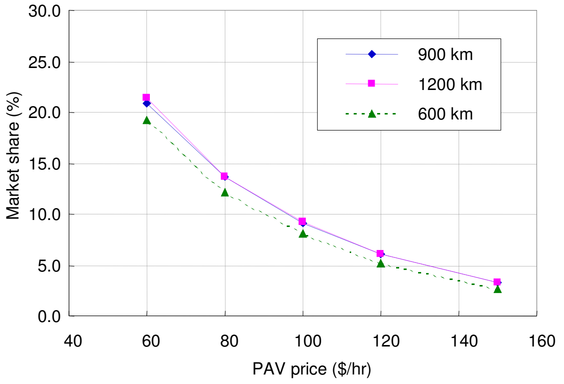


Figure 16: Result of Scenario R_L and R_H

Tradeoff Study for Technology Selection

On top of the sensitivity analyses of vehicle design requirements, the method provides a powerful capability to enable a quantitative tradeoff study for a technology selection problem, which has been impossible in the past.

Effect of Easy-to-fly Technology

In Scenario C, the easy-to-fly technology was removed from the baseline PAV, which would result in the same percentage of pilots as presently. Scenario C assumes that 0.25% of the adult population is qualified to operate a PAV while Scenario B assumes very audacious number, 50%. As expected, the easy-to-fly technology had the largest effect on the market share, which can be evidenced by huge gap in Figure 17. While the advantages of enabling easy-to-fly technologies are intuitive, the simulation illustrated the effect quantitatively. Now a decision maker can measure the importance of the technology. For example, the easy-to-fly-ON PAV (Scenario B) at $150/hr and the easy-to-fly-OFF PAV (Scenario C) at $100/hr can be compared.

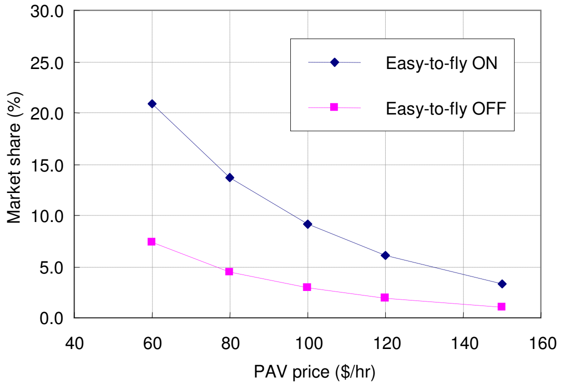


Figure 17: Result of Scenario C

Figure 18 is a counterpart of Figure 12. It shows the effect of removing the easy-to-fly technology in a highly visualized format. Travelers who still select PAVs become much more rare. Interestingly, other trends were preserved; agents still find PAVs most useful for trips between 350 and 900 km.

X-axis: distance in km, Y-axis: annual household income in USD

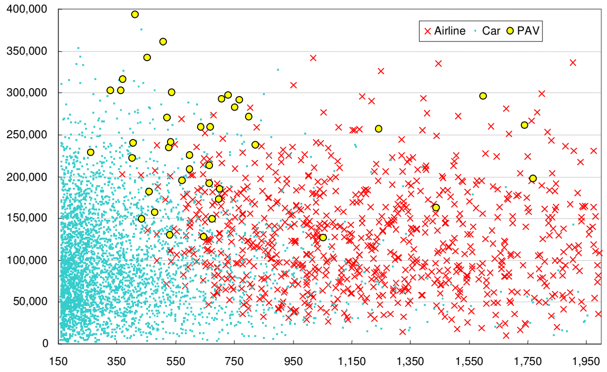


Figure 18: Market Space of Scenario C ($150/hr)

Effect of Roadability

Scenario D explored the effect of incorporating a roadability function to the baseline PAV, making it a dual-mode PAV. The primary concern for manufacturers would be the extent of increase in market share that can be achieved through dual-mode vehicles. The benefit in market share can be compared through a quick feasibility study against the cost increase to achieve the roadability function, as shown in Figure 19. The first impression on this figure is that the gap between two curves is smaller than that of Scenario V_H. This means, if other conditions were kept the same, increasing cruise velocity by 50 km/hr would be a better engineering decision than making a vehicle roadable.

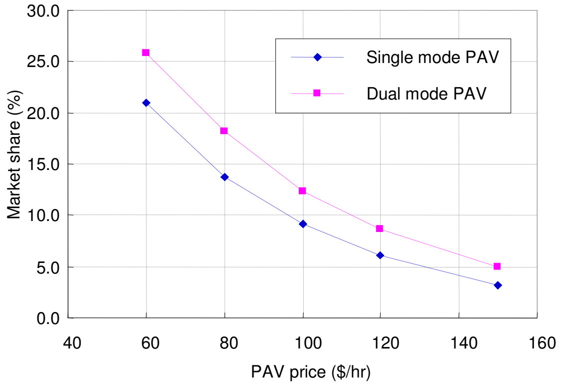


Figure 19: Result of Scenario D

Two 'market space' plots are prepared in Figure 20 and 21 for further investigation. The first plot is for a dual-mode PAV scenario, with PAV price of $150/hr, while the second one assumes a single-mode PAV with a price of $129/hr. This value was obtained by solving the regression equation, which appears in Figure 11, for x such that y value is equal to the same market share value for dual-mode PAV with price of $150/hr. Indeed, two simulations resulted in the same market share. However, a difference in market space could be found. Dual-mode PAVs competed primarily with automobiles on the medium-length routes for high income agents. Single-mode PAVs competed more with commercial airlines.

X-axis:distance in km, Y-axis: annual household income in USD

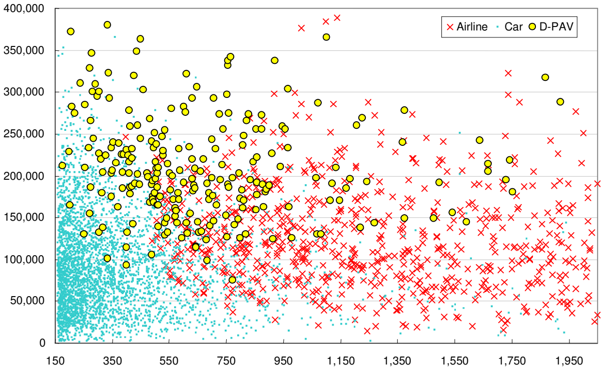


Figure 20: Market Space for Dual-mode PAV with $150/hr

Figure 21: Market Space for Single-mode PAV with $129/hr

Other comparisons can be performed with relative ease. For example, a concept tradeoff between a slow dual-mode PAV and a fast single-mode PAV is now possible. Both vehicles can be placed in the simulation together to demonstrate competitive advantage, or they can be run separately, just like the present scenarios, to determine which is better in isolation.

Conclusion

The purpose of this research is to expand our boundaries of the knowledge of the personal air vehicle (PAV) design space. It was contended and emphasized that a PAV design problem is not only a system-of-systems problem but also a decision-making problem. Any PAV system should be understood in the context of the national transportation system (NTS), and correct decision-making is critical in generating design requirements, which will lock in the next development efforts as alternatives concept vehicles are being formulated.

As a potential approach to address this challenge, an integrated decision-making method was proposed. The method employed an agent-based modeling and simulation (ABM/S) technique. The core of ABM/S was to make a virtual world that imitates the NTS. The model incorporated travelers' behavioral characteristics, the market's response, the infrastructure environment, as well as various kinds of uncertainty, which ultimately connect to the overall system effectiveness. This virtual world was implemented in a computer code before Monte Carlo simulations were carried out and responses from heterogeneous agents were monitored and scrutinized through the sensitivity analyses.

The method made it possible to measure the leverage effect on the NTS due to changes in top-level PAV design requirements. Furthermore, the effect of the system technology could be evaluated for the technology tradeoff study. Therefore, this method is logically extended to a capability enabling comparison among different vehicle concepts quantitatively, which has never been done before.

The power of the method could be further enhanced and evolved for sophisticated real decision-making problems, provided that all participants from multiple domains – vehicle manufacturers, service providers, customers and policy makers from government agency – share this method as a tool to guide an integrated decision-making process. With this powerful method, designers can extract essential technical requirements that allow polishing of concept vehicles; policy makers can investigate the infrastructure impact of new systems; and vehicle manufacturers can perform economic analysis based on their own business assumptions.

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