9th AIAA/ISSMO Symposium on Multidisciplinary Analysis and Optimization
4-6 September 2002, Atlanta, Georgia

AIAA 2002-5620

SYSTEM-OF-SYSTEMS MODELING FOR PERSONAL AIR VEHICLES

Daniel DeLaurentis, Taewoo Kang, Choongiap Lim, Dimitri Mavris, Daniel Schrage
Aerospace Systems Design Laboratory (ASDL)
School of Aerospace Engineering
Georgia Institute of Technology, Atlanta, GA 30332
http://www.asdl.gatech.edu

Abstract

On-going research is described in this paper concerning the development of a methodology for adaptable system studies of future transportation solutions based upon personal air vehicles. Two challenges in this research are presented. The challenge of deriving requirements for revolutionary transportation concepts is a difficult one, due to the fact that future transportation system infrastructure and market economics are inter-related (and uncertain) parts of the equation. Thus, there is a need for a macroscopic transportation model, and such a task is well suited for the field of techniques known as system dynamics. The determination and visualization of the benefits of proposed personal air vehicle concepts for individuals presents a second challenge. In this paper, the primary benefit metrics that serve as system requirements for personal transportation applications are the Doorstep-to-Destination travel time-savings and net present value of utilizing the new transportation option as compared to a conventional transportation mode. The modeling and determination of these metrics, the synthesis of vehicle characteristics, as well as existing travel statistical data are integrated into the system model to enable visualization of the design space and to guide the design space evolution through sensitivity assessment. This individual traveler-based analysis is referred to as a microscopic model, and interesting results from its execution are reported. The results indicate the level and direction of technology progress required to create economically viable personal air transportation architectures.

Nomenclature

CTOL	Conventional Takeoff and Landing
D-D	Doorstep-to-Destination
DOC	Direct Operating Cost
OEC	Overall Evaluation Criterion
PAV	Personal Air Vehicle
RSE	Response Surface Equation
RSM	Response Surface Methodology
SSTOL	Super Short Takeoff and Landing
STOL	Short Takeoff and Landing
UTE	Unified Tradeoff Environment
VTOL	Vertical Takeoff and Landing
VTSI	Vehicle Time Saving Index

Introduction

System-of-systems problems contain multiple, interacting, non-homogeneous functional elements, each of which may be represented as traditional systems themselves. This collection often exists within multiple hierarchies and is not packaged in a physical unit. Thus, according to this preliminary definition, an aircraft is a system while a network of personal aircraft operated collaboratively with ground systems for improved transportation is a system-of-systems. In such a problem, for example, there are multiple, distinct vehicle types, ground and air control networks, economic drivers, etc.

The increase in complexity brought by system-of-system problems challenges the current state-of-the-art in conceptual design methods. The purpose of this paper is to report on design methodology research for this type of problem focused at *the conceptual level*. How should designers cast such complex problems when so much uncertainty and ambiguity exists? This question is explored, in both generic terms and through the application of ideas to the personal air vehicle (PAV) challenge, including the definition of associated key characteristics and modeling capabilities. Particular attention will be given to the formulation and execution of conceptual design methods for such problems that are adaptable and amenable to rapid visualization.

What is meant by PAV? PAVs are not today's General Aviation (GA) aircraft. Nor are they "Jetsons"-like imaginations. PAVs are envisioned as vehicles of the future (30 years) that may operate synergistically with ground and other air infrastructure to dramatically improve individual mobility within the larger transportation environment. Thus, understanding how the individual PAV interacts with the larger system is critical.

Simulating the environment in which a PAV will operate is a difficult task, particularly because there are many time-variant factors that directly and indirectly impact the environment. Previous attempts at characterizing personal mobility solutions often encountered the limitation of producing 'static' results for which updating of models and evolving of assumptions was difficult.[1,2] To address this shortcoming, the overall model of the PAV environment is categorized into a *microscopic* model and a *macroscopic* model. The microscopic model refers to an isolated, single-user travel simulation using a PAV concept. This microscopic model (or collections thereof) will then be embedded in the macroscopic model, which portrays the dynamic mass traffic capacity model of the specified location. This dynamic macroscopic model will provide feedback caused by such things as overcapacity, as shown in Figure 1 below.

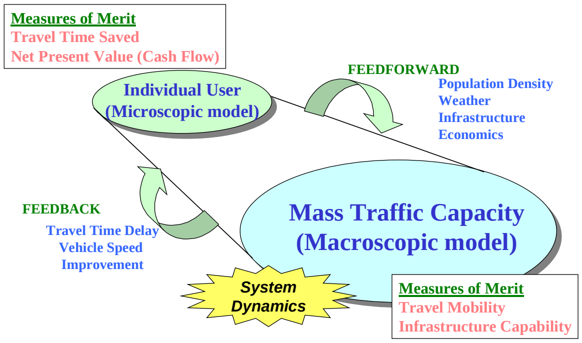


Figure 1: Overall PAVE Modeling Environment

The primary focus of this paper is on the microscopic model that is created by a spreadsheet-based "benefits visualization tool". This tool provides a unified tradeoff environment that simulates the effectiveness of a PAV for a single user's travel, and serves as part of the overall model. A method intended for connecting the two models is also discussed in this paper, as is the anticipated capability of the overall model.

The most important anticipated capability is impact assessment of other related technologies interjected on the PAV system architecture. One such area of technology of keen interest is NASA's Small Aircraft Transportation System (SATS) program. At completion, the combined model should be adaptive to scenario changes and will evolve as new data and new ideas enter the system-of-systems construct.

Technical Approach

The microscopic model presented in this paper comprises an equation set. The resulting tool has the purpose of simulating a single-user's travel effectiveness using a PAV, and thus, provides a unified tradeoff environment. The environment consists of three main components: interface, performance computations, and economic computations. These components are described next.

Interface

The interface component acts as a mediator between the user and the benefits visualization tool, and constitutes three profiles: vehicle/mission, economics, and location. The microscopic model will compute the travel performance for the individual user based on the specified vehicle/mission profile and the travel economics based on the specified economic profile. Meanwhile, given a specified user's location profile, a local traffic capacity model based on that profile can be created using a simulation technique such as system dynamics or Agent-Based Simulation. This larger model serves as the platform for the macroscopic mass traffic capacity model.

Vehicle/Mission Profile

The Vehicle/Mission profile interface allows users to select the desired vehicle options and mission options for analysis. PAV options have been categorized into 4 groups based on their takeoff and landing distance; VTOL (100 ft), SSTOL (500 ft), STOL (1000 ft), and CTOL (2000 ft). A definition of each PAV group is provided in Nomenclature section. Each group is divided into two modes; single mode and dual mode PAVs. Single mode PAVs are PAVs that require alternate ground vehicles such as cars or taxis to transport users to the PAV facilities. Dual mode PAVs are PAVs that operate as ground vehicles as well as air vehicles. Each mode is then divided into two options; fast and slow PAVs. Hence, there are a total of 16 PAV options as shown in Figure 2 below:

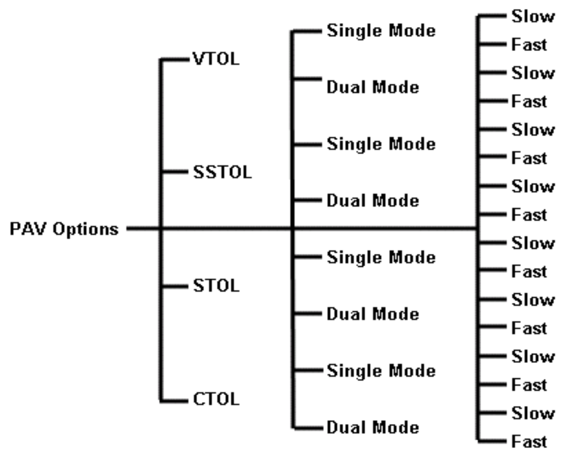


Figure 2: Categorization of PAV Options

The PAV generic mission profile is depicted in Figure 3. Each PAV option must complete the main mission from access portal A to access portal B, that is, from one airport location to another. Selection of a single mode PAV is accompanied by either a personal car or a rental car to get to and from the airport. Meanwhile, selection of a dual mode PAV does not require additional ground vehicle. For comparison sake, a user is able to select a ground vehicle (personal car or rental car) and a commercial airline to complete the main mission on top of the 16 PAV options. In this way, the resulting tool can truly be considered a multi-modal options analysis.

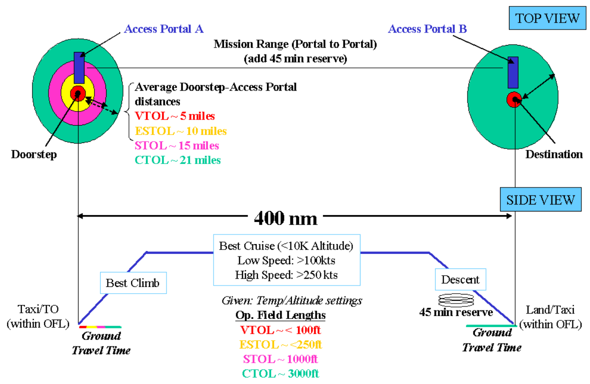


Figure 3: PAV Mission

The next important interface is the mission profile, which identifies the profiles for the user's typical travel. The input options are shown in Figure 4 below. The range for the typical distance of 100 to 500 nm is selected based on the most commonly flown distance for general aviation aircraft, inter-city driving trips, and regional commercial air travel. 'Trips made per week' refers to one-way trips made either to and from the workplace for the whole week. For instance, a typical 5 working days week constitutes of 10 trips per week. The number of 'PAV-pooling' passengers refers to the number of passengers onboard that share the direct operating cost of the PAV, similar to sharing gas cost in a car pool.

Mission Options	*Selection*	
Typical Range (100 - 500 n.m.)	200	n.m.
Trips Made Per Week (6-22)	10	trips/week
Number of 'PAV-pooling' passengers (max 4)	2	passengers

Figure 4: Mission Profile Inputs

The final set of vehicle/mission profile options concerns the vehicle economics. The user is allowed to determine the specific vehicle financing terms, as shown in Figure 5. Financing terms significantly influence the viability of the PAV. These financing options are down-payment for the PAV, loan interest rate, loan period, and predicted life span of the PAV.

Vehicle Economics Options	*Selection*	
Downpayment (as fraction of vehicle acq. cost)	15	%
Loan Interest Rate (Annual)	9	%
Loan Period	12	years
Predicted Lifespan of Vehicle (50 years max.)	40	years

Figure 5: Vehicle Economics Profile Inputs

Information obtained from this profile will be used to compute the performance of the PAV option relative to a baseline transportation mode, as discussed in later section.

Economic profile

The current economic model is an individual purchase model. Other models, such as fractional ownership and air taxi are also being investigated. This economic profile interface requests financial and economic information of the individual user in order to compute the viability of the PAV option. This is because the measure of merit for the microscopic model is based on the 'value of time saved' concept, which will be discussed later. As shown in Figure 6, a user is allowed to input his/her annual household income as well as values for predicted annual percentage increase/decrease of annual household income for the first 15 years from present day, in steps of 5 years.

My current annual income (in US Dollar) is:	$90,000 <input top>
Predicted income change per year in first 5 years (+/-) is :	5.0% <input top>
Predicted income change per year in following 5 years (+/-) is :	5.0% <input top>
Predicted income change per year in following 5 years (+/-) is :	5.0% <input top>

Figure 6: User Economic Profile Inputs

Information obtained from this profile and the performance computation based on vehicle/mission profile will be used to compute the 'value of time saved' by utilizing the PAV option as compared to a baseline transportation mode. This metric will be the measure of merit for the microscopic model.

Location profile

The location profile interface requests the user's typical origin and destination information, in terms of population density, weather, and infrastructure availability. The population density is categorized based on U.S. Census categorization. Meanwhile, weather is categorized into six weather group regions in the U.S based on studies by the Office of Safety and Mission Assurance (OSMA). Infrastructure availability is categorized more intuitively by simply asking the user to rate the infrastructure availability in a scale from 1 to 5, with 4 being least available and 5 being "Uncertain" (where a defaulted value will then be used).

Code	Description
Metro counties:	
1	Central counties of metro areas of 1 million population or more.
2	Counties in metro areas of 250,000 to 1 million population.
3	Counties in metro areas of fewer than 250,000 population.
Nonmetro counties:	
4	Urban population of 20,000 or more.
5	Urban population of 2,500 to 19,999.

Figure 7: Population Density Categorization

Code	States
1	CT, MA, ME, NH, NJ, NY, PA, RI, VT, WV
2	AL, AR, DE, FL, GA, KY, LA, MD, MO, MS, NC, SC, TN, VA,
3	IL, IN, MI, MN, OH, WI
4	IA, ID, MT, ND, NE, KS, SD, UT, WY
5	AZ, CA, CO, NM, NV, TX
6	OR, WA

Figure 8: Weather Region Categorization

Performance Ccomputations

Vehicle performance is dictated by parameters such as vehicle speed, empty weight, fuel weight, single or dual mode, and field length categories. These parameters will be used to compute the key performance metric: Doorstep-to-Destination Time.

Doorstep-to-Destination Time (D-D Time)

Doorstep-to-destination time refers to the total travel time from the origin location to the destination location, including all the delay times and travel times from origin and destination to access portals. For a PAV "world", the access portal refer to any facility that is capable of handling a PAV, ranging from helipads to private runways to regional airports. Breakdown of the D-D time is shown below:

Equation 1: D-D Time Computations

$$\text{D-D Time} = \alpha + \beta + \delta + \varepsilon + \varphi$$

$$\text{where} \quad \alpha = \text{Travel Time}_{\text{Doorstep to Portal A}} = \frac{\text{Ground Distance}}{\text{Avg. Ground Vehicle Speed}}$$

$$\beta = \text{Travel Time}_{\text{Wait Time at Portal A}} = \text{Vehicle Specific}$$

$$\delta = \text{Travel Time}_{\text{Portal A to Portal B}} = \frac{\text{Travel Distance}}{\text{Avg. Vehicle Air Speed}}$$

$$\varepsilon = \text{Travel Time}_{\text{Wait Time at Portal B}} = \text{Vehicle Specific}$$

$$\varphi = \text{Travel Time}_{\text{Portal B to Destination}} = \frac{\text{Ground Distance}}{\text{Avg. Ground Vehicle Speed}}$$

Assumptions for D-D Time Computation

1. The 16 modes of PAV, divided into groups of 4 main categories (VTOL, SSTOL, STOL, and CTOL) have specified average distances from doorstep and destination to portals of 5, 10, 15, and 21 miles respectively. Average distance to a commercial airport is assumed to be 30 miles.
2. Due to environmental and operational constraints, it is assumed that dual mode PAVs will not be allowed to operate from a populated residential or business location in spite of the idealized 'operable from anywhere' concept of dual mode vehicles.
3. The wait time at access portals is fixed at 30 minutes for each of the PAV option whereas for commercial airlines option, the wait time is fixed at 2 hours upon departures and 1 hour after arrivals.
4. Average speed of ground vehicles to and from access portals is specified as 50 mph. Average speed of personal autombile as a main travel mode is specified as 65 mph. The ground speeds of dual mode PAV are extracted from the vehicle database.

Economic Computations

Cash Flow Analysis

In the engineering field, cash flow analysis is most commonly used in describing the predicted profitability of a project. Results from this analysis are depicted in a cash flow graph as a function of time (unit of time may be days, months, years, etc depending on the size and scale of the project/investment). This graph provides crucial information such as break-even point, net profit, sunk cost, capital investment, payback period, profitability, and utilization period to aid decision-makers in making intelligent and financially-sound decisions. Definitions for important economic terms relevant to the cash flow analysis are provided below (see Ref. 3 and Ref. 4 for detailed definitions and equations):

Cash flow is the difference between receipts and expenditures, which may have either negative (i.e. expenditures exceeds receipts) or positive values (i.e. receipts exceeds expenditures) at any point of time.

Cumulative cash flow is the accumulation of cash flows since the beginning of the project/investment to the termination of the project/investment, which is also the y-axis data plot of the cash flow analysis graph.

Break-even point is the first point of time when cumulative receipts exactly equates cumulative expenditures, where value of cumulative cash flow at that instance of time is zero.

Net profit is the value of a positive cumulative cash flow in the cash flow analysis at the final point of time when the project/investment is salvaged or terminated.

Sunk cost is the most negative value of cumulative cash flow in the cash flow analysis, typically referring to cumulative cash flow at the final point of the capital investment.

Capital investment period refers to the period when capital investments are being paid for, which is from the beginning of the project/investment to the point of time when sunk cost is incurred.

Payback period refers to the period when the sunk cost is gradually paid back by excessive cumulative receipts, which is right after capital investment has been totally accounted for to the break-even point of time.

Profitability refers to the period when the project/investment is having a positive cumulative cash flow, which is from the break-even point to the final point of time in the cash flow analysis.

Utilization period refers to the period when the project/investment is active and generating cash flows.

Economic Assumptions for PAV Concept

Similar to any other business project or investment, the economic viability of a PAV concept can be depicted using a cash flow analysis. Accompanying the cash flow analysis for any particular PAV concept is a list of critical assumptions that define the economics of the concept:

1. All cash flows are discounted to present value based on real interest rates, which includes the effects of inflation. Values for estimated annual inflation rate and annual nominal interest rate are specified to compute the expected annual real interest rate as follows:

Equation 2: Real Interest Rate Computation

$$r_o = \frac{r - f}{1 + f}$$

where r_o = real interest rate

r = nominal interest rate

f = inflation rate

2. Cumulative cash flow analysis for users' selected PAV options as well as the baseline vehicle options are computed based on the selected vehicle's performance.
3. The forms of expenditures for the cash flow analysis are vehicle financing (interests and installments) and direct operating costs. The form of receipts for the cash flow analysis is the value of time saved by utilizing a PAV option as compared to a baseline transportation mode (further discussed in later sections). The cumulative cash flow analysis for the baseline transportation mode is comprised of only expenditures because there is no value of time saved.
4. There are two baseline transportation modes; personal automobile and commercial airliner. For travel distances from 100 to 500 nm, an optimum baseline is selected on the basis of shortest travel time and lowest travel costs (see Assumption 5 below) such that the comparisons between baselines and PAV options are most accurate. Figure 9 shows that optimal travel time for distances from 100 nm to 300 nm is by car whereas commercial airliners typically optimize travel time for distances greater than 300nm. Table 1 further reinforces that statement by showing that driving is cheaper for distances from 100 nm to 300 nm whereas flying is more cost effective for distances above 300 nm. Hence, the baseline transportation mode are personal automobiles for distances ≤ 300 nm and commercial airliners for distance >300 nm.

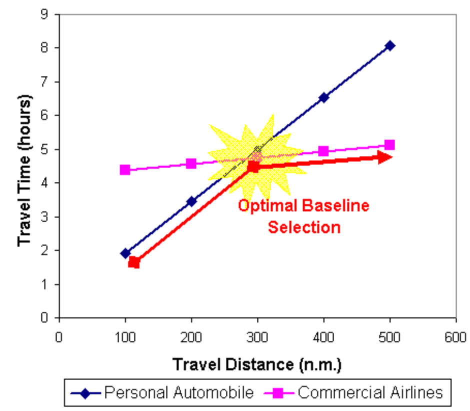


Figure 9: Travel Time Analysis for Baseline Modes

Table 1: Travel Cost Analysis for Baseline Modes

Travel Distance (nm)	100	200	300	400	500
Cost Difference Relative to Car ($)	+116.79	+76.22	+36.12	-3.52	-42.69
Optimal Option	Car	Car	Car	Plane	Plane

5. The cost of utilizing personal automobiles is rated at $0.35 per statute mile of travel[5]. Cost of utilizing commercial airlines is computed from a quadratic polynomial fit of an array of current air ticket price list referenced from Ref. 6. Cost of utilizing rental cars or cabs to and from commercial airports is estimated at $2.00 per statute mile of travel as an averaging value for first mile cost (varying from $2 to $3) and $0.40 per quarter mile rate [7, 8].
6. Salvage value for vehicle at the end of vehicle utilization is fixed at 15% of initial vehicle acquisition price.

There are two versions of cumulative cash flow analysis; direct cumulative cash flow and adjusted cumulative cash flow. Direct cumulative cash flow is computed directly using data from the vehicle database for both PAV options and baseline options. The direct cumulative cash flow of PAV options may show either a net profit or net loss relative to the baseline cash flow, indicating a profitable or unprofitable PAV option (see Figure 10). Adjusted cumulative cash flow is computed for the PAV options relative to the selected baseline option. This is based on the assumption that cash flow for the baseline transportation mode is regarded as incurred cost to provide users' mobility. Hence, subtracting this incurred cost from the PAV option cumulative cash flow yields an adjusted cumulative cash flow that reflects the relative financial gain or loss due to the adoption of a PAV concept (see Equation 3 and Figure 11). An adjusted break-even point occurs when the PAV option breaks even with the baseline cash flow in Figure 10, and is equivalent to the conventional break-even with the X-axis in Figure 11.

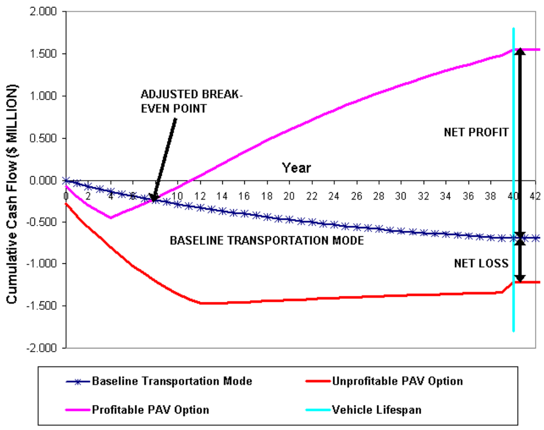


Figure 10: Direct Cumulative Cash Flows

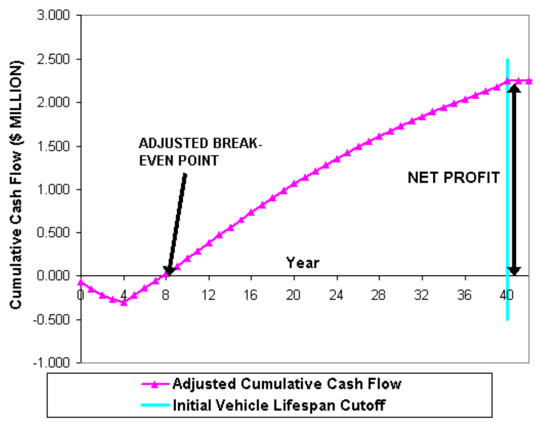


Figure 11: Adjusted Cumulative Cash Flow

Equation 3: Adjusted Cumulative Cash Flow Computation

$$\begin{aligned}&\text{Adjusted Cumulative Cash Flow, ACF}\\&= \text{PAV Option Cum. Cash Flow - Baseline Cum. Cash Flow}\\&\text{where ACF can have negative OR positive values}\end{aligned}$$

Value of Time Concept

As mentioned earlier, the only form of receipts for the cash flow analysis is the value of time saved by utilizing a PAV option as compared to a baseline transportation mode of either personal automobiles or commercial airlines. Value of an individual's time is a continuously debatable issue as one's worth of time truly depends on his/her personal evaluation and character. Nevertheless, it is reasonable to impose a numerical value of time based on how much money an individual makes on a regular working hour. Hence, the equation for value of time is:

Equation 4: Value of Time Computation

$$\begin{aligned}&\text{Value of Time (in units of dollars per hour)}\\&= \frac{\text{Annual Income}}{\text{2080 working hours per year}}\end{aligned}$$

For example, the value of time for an individual making $52,000 a year is $25 per hour.

Given a PAV option and a selected baseline option, the Doorstep-to-Destination times can be computed using the equation in Equation 1 along with the relevant assumptions and data from the vehicle database. Using these D-D travel times of the baseline and the PAV, a metric named Vehicle Time Saving Index (VTSI) is created:

Equation 5: Vehicle Time Saving Index (VTSI) Computation

$$\text{VTSI} = \frac{\text{D - D Time}_{\text{Baseline}} - \text{D - D Time}_{\text{PAV Option}}}{\text{D - D Time}_{\text{PAV Option}}}$$

VTSI is a dimensionless value that represents the amount of time saved for every utilization hour of a PAV option as compared to utilizing the baseline option. A negative value for VTSI indicates that the PAV option is slower than the baseline and should not be considered in the first place. VTSI will then have a value of zero. From the definition of VTSI and value of time, the value of time saved by utilizing a PAV option can be simply defined as:

Equation 6: Value of Time Saved Computation

$$\begin{aligned}&\text{Value of Time Saved (in dollars)}\\&= \text{VTSI} * \text{Hours of Utilization} * \text{Hourly Value of Time}\end{aligned}$$

Cash Flow Computation for PAV Concept

With the economics assumptions and value of time concept described above, the cumulative cash flows for PAV concepts are computed as shown in Equation 7.

Equation 7: Cash Flow Computation

$$\begin{aligned}&\text{Cumulative Cash flow} = \text{Cumulative Profits - Cumulative Costs}\\&\qquad = [\text{VTSY} + \text{Cumulated Profits}] - [\text{TCPY} + \text{Cumulated Costs}]\\&\text{where:}\\&\text{VTSY} = \text{Value of Time Saved per Year for current year}\\&\quad = \left(\frac{\text{Value of Time}}{\text{1 hour}}\right) * \left(\frac{\text{Hours Saved by using PAV per year}}{\text{1 year}}\right)\\&\quad = \left(\frac{\text{Income Fluctuation Rate} * \text{Annual Income}}{\text{2080 working hours per year}}\right)\\&\quad\quad * \left(\text{Hours Saved per day} * \frac{\text{260 working days}}{\text{1 year}}\right)\\&\text{TCPY} = \text{Total Cost Per Year}\\&\quad = \text{Annual Capital Payment} + \text{Adjusted Annual Direct Operating Cost (DOC)}\\&\quad = (\text{Annual Interest Payment} + \text{Annual Installment}) + \text{Adjusted Annual DOC}\\&\quad = \left[(\text{Loan Interest Rate} * \text{Loan Balance}) + \frac{\text{Post Downpayment Balance}}{\text{Loan Period, n}} \text{for n years}\right]\\&\quad\quad + \left[\text{Real Interest Rate} * \frac{\text{DOC}}{\text{1 hour}} * \frac{\text{Hours}}{\text{1 Trip}} * \frac{\text{Number of Trips}}{\text{1 week}} * \frac{\text{52 weeks}}{\text{1 year}}\right]\end{aligned}$$

Implementation

Unified Tradeoff Environment (UTE)

The various equations are merged to form a benefits visualization tool. This tool provides a unified tradeoff environment that facilitates the parameterized requirements forecasting and benefits estimation of a Personal Air Vehicle Exploration (PAVE). Further, the tool forms the foundation for a system dynamics study of the larger system-of-systems, which is the long term objective of this line of research. This UTE must be able to integrate the performance and economic attributes such that an Overall Evaluation Criterion (OEC) can be computed. This is done via the value of time saved concept, which translates the PAV option D-D time (totally dictated by vehicle performance) to a relative economical gain or loss in the cash flow analysis.

Parameterized Pave Requirements Forecasting

It is of interest to quickly and accurately determine the PAV requirements necessary to achieve profitability for a given segment of users. For initial studies, the technology and infrastructure assumptions used are representative of a future time when PAVs are widely accepted and used by the general public, much like automobiles in current time. Using Response Surface Methodology (RSM)[4] and the benefits visualization tool as the analysis engine, this parameterized PAV environment is created with the main objectives being:

i. To revalidate relationships between performance and economics attributes as prescribed by the assumptions made
ii. To generate PAV requirements for use by vehicle designers, as well as the relative sensitivity of these requirements to the various assumptions
iii. To identify key technology areas for succession of a PAV concepts based on objectives i and ii

A list of 7 parameters is identified through brainstorming and trial runs, as shown in Table 2. These parameters are selected based on their sensitivities to the computation of travel time and value of time saved.

Table 2: Requirement Parameters and Ranges

Description	Symbol	Unit	Lower	Baseline	Upper
Mission Requirements					
Mission Range	S	mi	100	300	500
Wait Time at Portal	TWAIT	hour	0.25	0.88	1.50
Vehicle Requirements					
Vehicle Air Speed	V	mph	200	350	500
Acquisition Cost	ACQ	$	50000	175000	300000
Direct Operating Cost/Hour	DOC	$/hr	15	68	120
User Requirements					
Personal Income	INC	$	75000	237500	400000
Utilisation	UTIL	trips/week	6	14	22

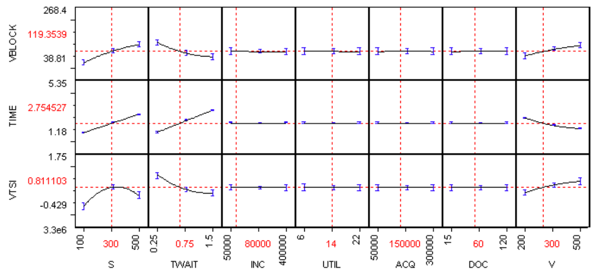
The ranges are carefully selected to ensure that the requirements space exploration covers all potential outcomes and includes interactions between the variables.

With these 7 variables, a 3-level Design of Experiment is created and a total of 79 simulation runs were made. The metrics of interest, shown in Table 3, are recorded and used to generate the Response Surface Equations (RSE). One of the responses that is of primary interests is adjusted break-even year (see earlier section for definition). However, due to the fact that a significant number of cases may not break-even when utilizing a PAV option, this metric will have a poor model fit and hence, cannot be used as a response. Instead, adjusted cumulative cash flows at year 5, 10, 20, and 30 are kept tracked of to depict adjusted break-even point whenever cash flow becomes positive. With the assumption that a fixed value of 40 years is used for vehicle life span, the net profit measures the cash flow at year 40 and may be either positive or negative, depending on whether the vehicle breaks even.

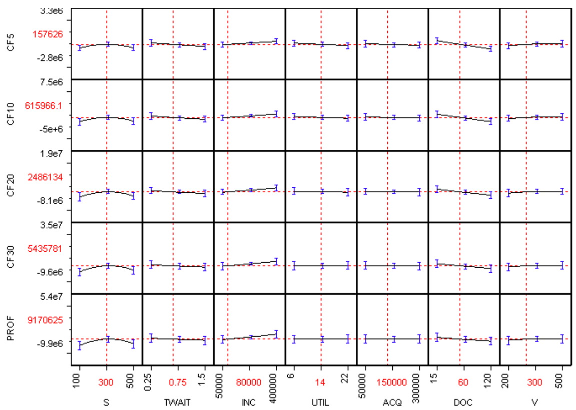
Table 3: Metrics of Interest

Description	Symbol	Unit
Block speed	VBLOCK	mph
Doorstep-Destination Time	TIME	hour
Vehicle Time Saving Index	VTSI	N/D
Cashflow at year 5	CF5	year
Cashflow at year 10	CF5	$
Cashflow at year 20	CF20	$
Cashflow at year 30	CF30	$
Net Profit	PROF	$

Visualization of the response surfaces is achieved through prediction profilers, which are displayed in Figure 12. The most outstanding observation from the prediction profilers is that a travel distance of 300 nm appears to be the most favorable travel distance for PAV concepts in terms of cash flows. The reasoning behind this observation is that for short distances, the economic benefits of travel time-savings by PAVs are not materialized. Meanwhile, for long distances, the high cruise speed of commercial airliners overcasts the significance of value of time saved by utilizing PAVs. This is further discussed in the later section for modeling of existing PAV environment. Also, as expected, Figure 12 a) clearly shows that improvement in vehicle cruise speed has a positive impact on VTSI, which is the only factor that dictates the receipts in the cumulative cash flow. VTSI is also significantly and negatively related to the wait time at portals. Subsequently, a higher cruise speed and a lower wait time will yield a higher cumulative cash flow at every point of time within the life cycle of the vehicle, as shown in Figure 12 b).



a) Prediction Profilers on Performance Metrics



b) Economic Metrics

Figure 12: Parametric Results: Prediction Profilers on Performance and Economic Metrics

To illustrate the utility of this RSM approach, an example using the contour profiler is shown in Figure 13 by plotting vehicle cruise speed (V) against wait time at portals (TWAIT). The two constraints imposed are the requirements to break-even in 5 and 10 years respectively. The contour lines ranging from 2 to 4.5 are the D-D time contour lines. The other mission factors are assigned values as shown in the table. For a given break-even point, say 5 years, the optimal cruise speed and wait time is desired such that a D-D time of 3.5 hours can be achieved. This is now an easy task as the tool provides slider bars that can be used to traverse along the plot until feasible space is found. For this particular example, the optimal tradeoff solution is when V lies at 286 mph and TWAIT at 0.96 hour or 57.6 minutes (marked by an X in the plot). Another practical example could be a user locating feasible space by trading off between vehicle speed and cost required to achieve break-even in year 10 for assigned values of his/her household income, utilization, and travel distance.

Many other scenarios can be generated from these prediction and contour profilers. These two tools present the analysis space as a parameterized tradeoff environment that is visibly comprehensible and easily manipulated. This promotes intelligent decision making by allowing the user to create scenarios where he or she can clearly visualize the impact of the parameters on the responses of interest and locate feasible space if any exists.

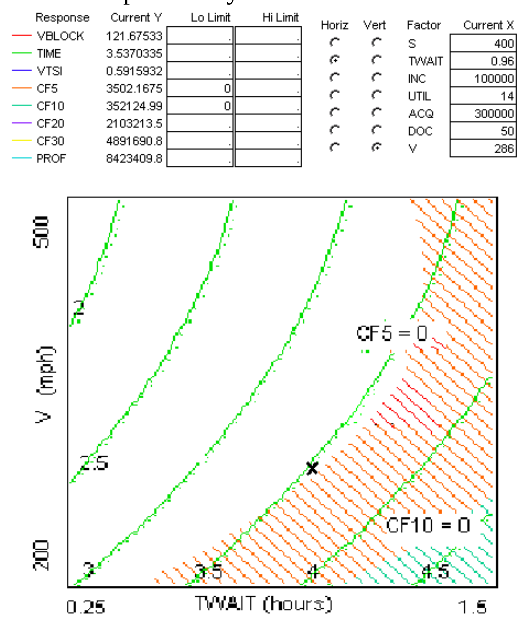


Figure 13: Contour Profiler

Existing PAV Concept Analysis Environment

The primary objective of this implementation of the benefits visualization tool is to compare the viability of several existing potential PAV options. Subsequently, a gap analysis can be performed to identify required technology infusions. Unlike the previous task, this task seeks to model a current PAV environment based on these existing PAV options, some of which are currently in service. However, only 6 out of the 16 PAV options have sufficient data available for the modeling, as shown below:

CLASS	MODE	SPEED	VEHICLE NAME
VTOL	Single	Slow	Robinson R-44
		Fast	-
	Dual	Slow	Boeing DART*
		Fast	-
SSTOL	Single	Slow	Groen Hawk 4
		Fast	Cartercopter Gyroplane
	Dual	Slow	-
		Fast	-
STOL	Single	Slow	-
		Fast	-
	Dual	Slow	-
		Fast	-
CTOL	Single	Slow	Lancair Columbia 400
		Fast	Eclipse 500
	Dual	Slow	-
		Fast	-

* Conceptual Design Only

Figure 14: Existing Potential PAV Options

Performance and economic data on these vehicles are researched and are entered into the vehicle database of the benefits visualization tool. These data are used for performance and economics computations described earlier. The primary measures of merit are D-D travel time-savings and net present value of utilizing the PAV option relative to the baseline transportation mode, represented by adjusted cumulative cash flow analysis. A set of assumptions accompany the computation of these two measures of merit:

1. All scenarios are modeled based on current existing vehicles, hence, employing current performance, technology, and economics assumptions.
2. For illustrative purposes, only 2 parameters are selected for sensitivity analysis while all others are kept fixed. These two parameters are household income and travel distance.
3. Household income is varied for two values: $200,000 and $350,000. These are realistic values based on tradeoffs between performance and costs of current technology level vehicles.
4. 5 scenarios are created for each household income level by varying travel distance from 100 nm to 500 nm in steps of 100 nm. This range is selected based on typical design and mission range of the existing potential PAV options.
5. Assumed values for mission and economics options (as discussed in Interface) are as follows:

Mission Options	***Values***
Trips Made Per Week (6-22)	14 trips/week
Number of 'PAV-pooling' passengers (max 4)	2 passengers
Vehicle Economics Options	*Values*
Downpayment (as fraction of vehicle acq. cost)	15.0%
Loan Interest Rate (Annual)	9.0%
Use Recommended Loan Period? If yes, type 'y' in box, else, enter loan period below.	y
Loan Period	12 years
Predicted Lifespan of Vehicle (50 years max.)	40 years
User's Economics Options	*Values*
Predicted income change per year in first 5 years (+/-) is :	5.0%
Predicted income change per year in following 5 years (+/-) is :	5.0%
Predicted income change per year in following 5 years (+/-) is :	5.0%
Other Economics Variables	*Values*
Annual percentage allocation for transporation	15.0%
Annual Inflation Rate	3.7%
Annual Nominal Interest Rate	7.0%
Annual Real Interest Rate	3.2%

Figure 15: Mission and Economics Assumptions

The net present values (NPV) of utilizing these 6 potential PAV options at the end of vehicle lifespan are obtained using the benefits visualization tool. Three observations can be made from the results shown below. First, it can be determined if the vehicle breaks even for a given travel distance. This is portrayed by the shaded cells in Figure 16 and Figure 17. Second, it can be shown which travel distance is most appropriate for PAV operations. Third, the net profit of the vehicles can be compared to identify which vehicle is most viable and/or profitable.

	40-Years Net Present Value for Income = $200,000 ($ Million)				
	100	200	300	400	500
R-44	-2.038	-1.094	0.263	-2.662	-4.055
DART	-0.591	0.008	2.305	0.319	-1.293
Hawk 4	-4.439	-4.117	-2.229	-4.621	-6.471
Cartercopter	-4.882	-2.702	0.599	-0.381	-0.988
Lancair	-2.513	-0.995	1.509	-0.269	-1.674
Eclipse 500	-4.350	-0.895	2.560	1.733	1.280

Figure 16: NPV of Vehicles for $200,000Household income

	40-Years Net Present Value for Income = $350,000 ($ Million)				
	100	200	300	400	500
R-44	-1.968	-0.008	2.674	-2.098	-3.984
DART	-0.591	3.613	7.818	4.570	2.179
Hawk 4	-4.037	-3.164	0.451	-3.387	-6.070
Cartercopter	-3.911	-0.091	5.691	4.021	3.208
Lancair	-2.050	0.786	5.346	2.453	0.418
Eclipse 500	-3.712	2.295	8.301	6.855	6.266

Figure 17: NPV of Vehicles for $350,000 Household income

The results above verify that household income is a critical factor in determining whether or not a PAV is viable. Less than one third of the combinations of vehicle and travel distance break even when the user makes $200,000 annually as compared to more than a half when the user makes $350,000. This is as expected since household income is a key player behind the value of time concept. However, the primary finding in these results is that PAV operations are most viable at 300 nm travel distance while worst at the extremely low travel distance of 100 nm. The reasoning behind this observation is that for low distances, the economic benefits of travel time savings by PAVs are not materialized. Meanwhile, for long distances, the high cruise speed of commercial airlines outweighs the delay time penalty at airports such that value of time saved by PAV becomes less significant. This observation is more apparent by plotting the adjusted cumulative cash flow of different travel distances for the Eclipse 500. The arrow in Figure 18 shows the cash flow trends from travel distance of 100 nm to 500 nm. Clearly, travel distance of 300 nm yields the highest adjusted cumulative cash flow for the Eclipse 500.

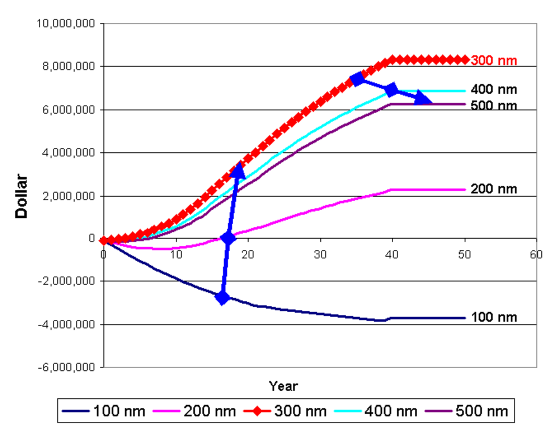
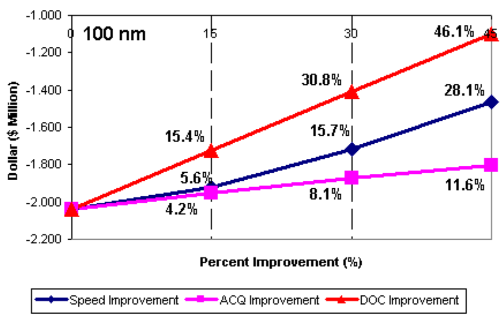
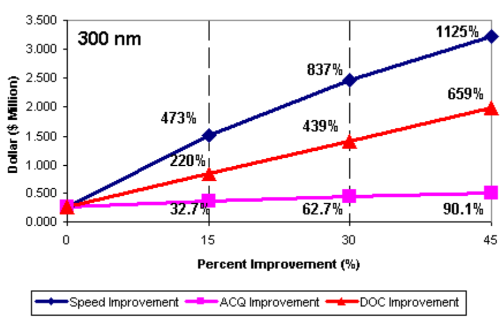


Figure 18: Adjusted Cumulative Cash Flow for Eclipse 500 for Varying Travel Distances (Household income = $350,000)

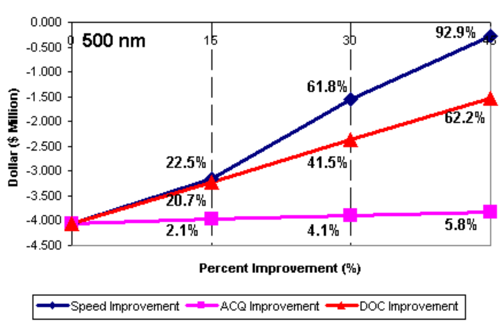
From the cash flow analysis for all vehicles, the Eclipse 500 is the most viable PAV option for both income levels, followed by the Boeing DART and the Lancair Columbia 400. One of the apparent observations made is that both the Eclipse and Lancair are CTOL general aviation aircraft. The Boeing DART, despite being a dual mode, high speed, light vehicle, is merely at its concept development stage. None of the VTOL or SSTOL vehicles currently in service fared well in the analysis. Despite the many advantages of VTOL concept, existing technologies had not made it possible for these vehicles to operate fast and cheap enough to compete with the much faster general aviation aircrafts. Having identified vehicle cruise speed and cost as two areas that require technology pursuit, a sensitivity analysis is performed on the VTOL R-44 light helicopter.



a) Travel Distance = 100 nm



b) Travel Distance = 300 nm



c) Travel Distance = 500 nm

Figure 19: Net Profit of R-44 in Year 40 with Varying Complexity Factors

A technology complexity factor is included in the cash flow analysis such that technology infusion allows improvements of 15%, 30%, and 45% on cruise speed (V), acquisition cost (ACQ) and direct operating cost (DOC). The assumptions made are similar to those given in Figure 15 and based on a $200,000 annual household income level.

Two main observations are made based on the technology sensitivity analysis. Firstly, for a short distance trip (100 nm), reduction in DOC yields the greatest increase in net profit whereas for a long distance trip (500 nm), increase in cruise speed yields the greatest increase in net profit. This can be explained by the fact that vehicle speed improvement will not significantly benefit the viability of the PAV option for short distance traveling since the air leg travel time is small compared to the ground leg travel time. Subsequently, reduction in DOC becomes the more pronounced factor in improving viability. Secondly, a reduction in the vehicle acquisition cost is least significant to improving vehicle viability. Hence, technologies that create fast and cost efficient vehicles at the expense of higher production cost are favorable in designing a viable PAV. From these observations, the new generation of PAV is anticipated to be a cost efficient vehicle that is relatively faster while possessing the advantages of VTOL capability.

Despite the analysis and observations made above, there is a clear recognition that major advancements in technology are needed to make PAVs affordable for large percentage of the populace (i.e. those who make less than $200,000). The identification of such technologies is the current prime directive of the NASA program that funded the research reported here.

System Dynamics Approach

The benefits visualization tool that was developed is a first step towards setting up a framework that integrates vehicle sizing capabilities, mission sensitivity studies and economic benefit metrics. It is a microscopic model of an individual traveler's trip from doorstep to destination, and serves as a requirement generator in the development of an ideal PAV. The system dynamics approach that follows describe the initial development of a macroscopic model that examines the feasibility and viability of an innovative product.

Systems dynamics is a methodology that enhances learning about complex systems, through such constructs as causal loop relationships between all the elements in the prescribed model as well as information feedback (Ref. 9). The causal loop diagram shown in Figure 20 is one such example, where the attractiveness of PAVs are tracked based on travel time and cost calculations. The arrows and polarities shown in the diagram represent the direction of causal influence and they contribute to creating both reinforcing and balancing feedback structures. An example of a balancing feedback is how an increase in the attractiveness of PAVs tends to increase the number of trips per day. That would increase the traffic volume and, due to the increased congestion, the travel time would now increase, causing a drop in the attractiveness in PAVs. An example of a reinforcing feedback would be how an increase in PAV attractiveness drives down the acquisition cost due to higher vehicle production, in turn increasing the attractiveness even further. The objective in such an example is to aid in the visualization of the dynamics involved in reducing average travel times and improving the mobility of future travelers.

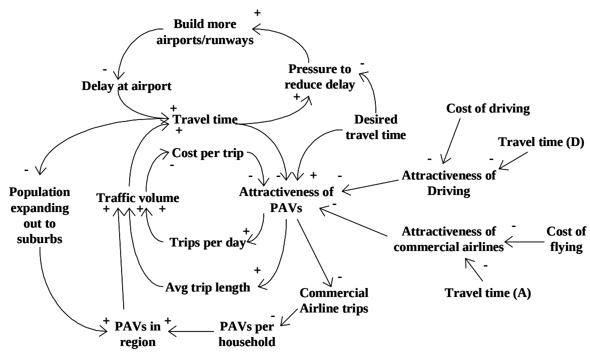


Figure 20: Causal loops diagram on the attractiveness of PAVs

Designers are often most familiar about simulation and modeling within their primary domain of interest and little of anything else. In a system-of-systems problem, formulation of simulation models no longer resides within one discipline but over multiple disciplines. One such example is demographics, which is essential in identifying the existence of a viable market but not easily understood outside the realm of government statisticians. Past demographic data can be easily put on a graph and extrapolated, but the dynamic trends would be hidden behind the charts. Within a system dynamics model, the dynamic trends between education level, income level and birth rate can all be explored as well. The people most likely to purchase and use PAVs in the next 20 years have already been born, and the data available is likely sufficient for designers to adequately model and predict future demand through the use of system dynamics.

Looking beyond the causal loop construct, the elements (or metrics) that subsist in the "Attractiveness of PAVs" must be identified. In the process of designing an evolutionary product, such elements can be easily assumed to be constant or interpolated from past data. For revolutionary concepts like PAV, however, designers have to place a keen interest in identifying the characteristics of the attractive opportunity. Those opportunities may present themselves in the form of new technologies, changes in demographics or lifestyles, or even as the result of unexpected occurrences such as an oil crisis. An example of the synthesis of such elements for PAV is provided in Figure 21.

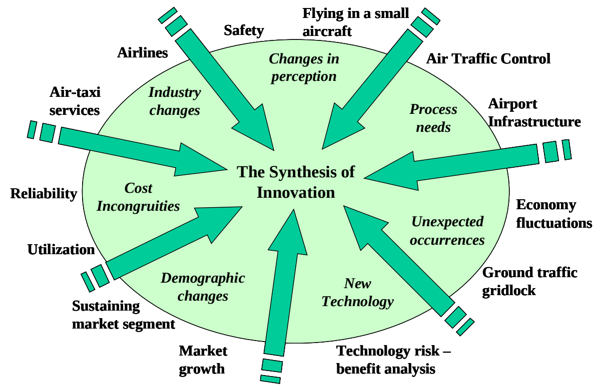


Figure 21: "Innovation Circle" for PAVs

Subsequently, particular metrics that eventually must be included in the system dynamics model must also be synthesized, as illustrated in Figure 22. This culminates in the creation of an Overall Evaluation Criterion (OEC), a construct that enables the evaluation of concept alternatives based on the defined system effectiveness metrics (Ref. 11). The formulation of the OEC is based on the understanding that any evaluation criterion depends on the actual system performance as well as the preferences of the system evaluator.

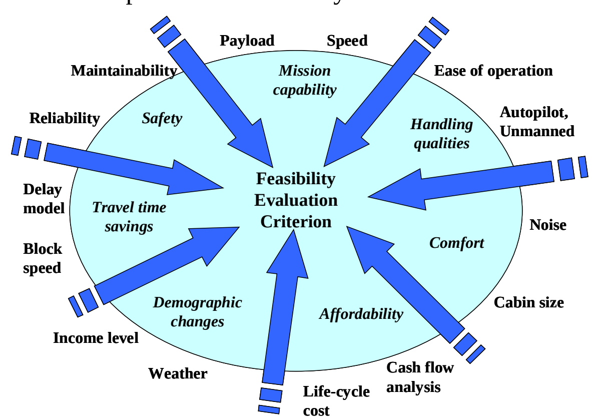


Figure 22: Multi-criterion feasibility assessment

Decision-maker preferences for the individual items in the OEC are represented through Importance Coefficients, and idealized system metric goals are listed as a direct comparison against the concepts. The OEC methodology was initially formulated as a tool aiding the direct comparison of concept alternatives and selection of the 'best' concept depending on the preferences of the system evaluator. In a market exploration study, the OEC is particularly useful because different combinations of the importance coefficient represent different opportunities within the commercial market. The various 'best alternatives' for each market segment can then be identified with the aid of the OEC.

Conclusion

An integration of transportation option analysis and life cycle economic analysis has been achieved for the purpose of creating a unified tradeoff environment for the examination of a system of personal air vehicles. A key facet of the manner in which the integration is done is the use of parametric techniques to create "what-if" environments that allow, for example, the extraction of vehicle requirements for use by vehicle concept designers and technology innovators. Initial findings indicate that dramatic improvement in vehicle speeds, operating costs, and acquisition cost will be required before such vehicles could be considered affordable means for improving the mobility of average travelers. Perhaps more importantly at the conceptual stages, however, was the demonstration of the capability to explore almost any trade study that decision-makers might envision.

The resulting tool is termed a microscopic model, since it focuses on the individual traveler and the associated economics. Current work is ongoing to embed this microscopic model in a macroscopic model that addresses the larger system-of-systems, including external feedbacks that will cause the attractiveness of the concepts to shift over time.

Acknowledgements

The authors wish to acknowledge the NASA Langley Research Center, and the PAV program monitor Mr. Mark Moore, for sponsorship of this research under contract NAS3-00179/L-70884-D.

References

1. Drake, H.M., Kenyon G.C., Galloway T.L., "Mission Analysis for General Aviation in the 1970's", AIAA Aircraft Design and Operations Meeting, CA, July 14-16, 1969.
2. Winich, R.M., "Intermodal Relationships", Proceedings of the Monterey Conference on Planning for Rotorcraft and Commuter Air Transportation, NASA Contractor Report 166440, February 1983.
3. Luenberger, D.G., Investment Science, Oxford University Press Inc., 1998.
4. Thuesen, G.J., Fabrycky, W.J., Engineering Economy, Prentice Hall, 1993.
5. McGrath, R.N., "NASA's Small Airplane Costs v. Airlines, Autos and the Economic Value of Time", Society of Automotive Engineers, 2002.
6. "An Agent-Based Simulation Tool for NASA SATS Program", NASA SATS Competition, Georgia Institute of Technology Student Entry, 2002
7. http://www.303taxi.com/html/taxi_rates.html, 2002
8. http://www.metwashairports.com/dulles/flyertaxirates.htm, 2002
9. Sterman, J.D., Business Dynamics: Systems Thinking and Modeling for a Complex World, Irwin McGraw-Hill, Boston, MA, 2000.
10. Myers, R.H., Montgomery, D.C., Response Surface Methodology: Process and Product Optimization Using Designed Experiments, John Wiley & Sons Inc., 1995
11. Mavris, D.N., DeLaurentis, D.A., "An Integrated Approach to Military Aircraft Selection and Concept Evaluation", Presented at the 1st AIAA Aircraft Engineering, Technology, and Operations Congress, Anaheim, CA, September 19-21, 1995.