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Approach to Characterize Mobility Through Modeling of Solution Spaces for Conceptual Aircraft

Daniel A. DeLaurentis,* Choongiap Lim,† and Taewoo Kang†
Georgia Institute of Technology, Atlanta, Georgia 30332-0150

The solution space for air-vehicle-based mobility architectures is a multidimensional space characterized by time–based and economic figures of merit. Successful vehicle design relies on the specification of a range of requirements within this space, but limited methods are available to generate these specifications in the context of future transportation scenarios. Thus, the development of new air vehicles for improved personal mobility is hindered by the inability to understand the nature, structure, and sensitivity of the solution space. A "mobility credit" concept is introduced in this paper, which that links the targeted increase in mobility with vehicle design. Doorstep-to-destination travel time and net present value are two expressions of the credit that are defined and explored. A methodology for adaptable systems analysis is then developed and implemented to locate and visualize preferable regions of this solution space that maximize the mobility credit, avoiding the premature selection of a point design that is counterproductive at the conceptual level. Simulation results are presented that parametrically quantify the preferred level of air vehicle (speed), infrastructure (delay time), and economic (direct operating cost) parameters within the solution space.

Nomenclature

$D-D_{\text{Time}}$	=	doorstep-to-destination travel time
d_1	=	travel distance from doorstep to access portal A
d_2	=	travel distance from access portal A to access portal B
d_3	=	travel distance from access portal B to destination
f	=	inflation rate
r	=	nominal interest rate
r_0	=	real interest rate
S	=	mission range
t_{d1}	=	travel time from doorstep to access portal A
t_{d2}	=	travel time from access portal A to access portal B
t_{d3}	=	travel time from access portal B to destination
t_{w1}	=	wait time at access portal A
t_{w2}	=	wait time at access portal B
V	=	air-vehicle average cruise speed
V_{BLOCK}	=	door-to-door block speed of travel
V_G	=	ground-vehicle average cruise speed

Introduction

MOBILITY is a term used to describe spatial movement, or the potential for movement, of people or cargo. It facilitates economic and social activity and is an important contributing factor to an individual's quality of life.[1] Levels of mobility are largely dependent upon the monetary, technological, and infrastructure resources that travelers have at their disposal. The advent of the automobile brought about a vast infrastructure with the construction of interstate highways that connect the metropolitan areas in the United States. The development of modern commercial air travel has produced the hub-and-spoke infrastructure that concentrates the required infrastructure in a small number of modes. Both modes of travel are rapidly approaching their limits in terms of levels of mobility provided in a safe manner for a large number of trip types.[2] Although research programs are under way to extend these limits, even modest estimates for the increase in demand result in a potentially untenable transport system in the future if the present paradigms remain.

New mobility solutions that exploit advanced air vehicles (as yet not in production) in an on-demand fashion are envisioned to enhance the mobility of a large portion of travelers with a minimum of new infrastructure. With an enhancement in mobility, travelers can choose to spend less time on travel over a given distance (or take longer trips in a given time), have more flexibility in where they live relative to workplace or daily activities, or travel in ways otherwise not currently possible or affordable. The increase in mobility, termed a "mobility credit," is a union of all three options and thus is a form of currency that can be spent based upon individual preference.

$$\text{Mobility Credit} = \text{time saved} \cup \text{flexibility gained} \cup \text{money saved}$$

In this context, the purpose of developing air-vehicle technology lies in enhancing mobility for future travelers.[3] More directly, the criterion for the evaluation of air-vehicle technology concepts should be the extent of their impact on mobility credit. Aircraft that are optimal with respect to traditional performance measures might be poor choices in this envisioned future of on-demand, near point-to-point travel. Thus, it becomes important to model the characteristics of the mobility credit and measure it through intermediary metrics such as doorstep-to-destination travel time and net present value. These metrics become the critical link to the aircraft design community.

The challenge of deriving requirements and selecting technologies for revolutionary transportation concepts that have a realistic probability of success is a difficult one. However, misguided vehicle design and technology investment can be an expensive consequence of not having the tools for exploration of the mobility solution space. There has been no shortage of innovative air vehicles proposed over the years to fill this demand for improved mobility. Too numerous to list or fully reference, they range from the conventional general aviation (GA) concepts, to practical hybrids such as the gyroplane,[4] to the exotic such as dual-mode flying-car concepts.[5] In many cases, however, these vehicles are a result of technology push and often have undesirable traits that accompany the one or two innovations. The connection to the larger transportation system was missing, and the design requirement set was incomplete. The future transportation system infrastructure, the vehicle performance, and the market economics are interrelated (and uncertain) parts of the mobility equation. As a result, the research challenges are in the areas

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*Research Engineer, Aerospace Systems Design Laboratory, School of Aerospace Engineering. Senior Member AIAA.

†Graduate Students, Aerospace Systems Design Laboratory, School of Aerospace Engineering. Student Member AIAA.

of complete problem formulation including system interactions and the building of useful transportation system analysis methodologies at the conceptual level.

The subject of this paper is the mathematical modeling of the primary mobility credit metrics that represents system requirements for personal transportation applications. The two metrics analyzed in detail are the doorstep-to-destination travel time savings and net present value of utilizing the new transportation option as compared to two conventional transportation modes. Models of these metrics, key infrastructure variables, as well as existing travel statistical data, are integrated into the system model to enable visualization of the multidimensional mobility solution space. The evolution of this solution space is explored through sensitivity analysis to create an understanding of the dynamics between the market, the technology, and the mobility credit provided. The results indicate the preferred vectors of technology progress required to create economically viable personal air transportation architectures. Particular attention is also given to the formulation of conceptual design methods that are adaptable and amenable to rapid visualization.

Research Context

At the maturity of the envisioned on-demand mobility system of the future is the personal-air-vehicle (PAV) concept. A PAV world would represent the extreme form of a fully distributed, on-demand air transport system. Its realization is bounded by today's concept of limited mobility through advanced GA aircraft on the one hand to science-fiction-like imaginations on the other. In between is perhaps the more likely future that foresees advanced air vehicles operating synergistically with ground and other air infrastructure to dramatically improve individual mobility within the larger transportation environment. Such a forecast is in concert with the NASA Small Aircraft Transportation System (SATS)[6] program, but even more aggressively staged. Although the eventual outcome is unknowable for sure, understanding how the PAVs characteristics interact with the larger system is the context of the current research.

Simulation of the future environment in which mobility concepts will operate, however, is a difficult task because of the effect of the many uncertain and time-variant factors. The start point is a collection of previous research that was focused upon characterizing personal mobility solutions in the context of mode choice and the value of time.[7–9] These studies, all dating to the early 1970s, provide insightful results that serve as a foundation for the current research. However, they encountered the limitation of producing static results for which updating of models and evolving of assumptions were difficult. Thus, model adaptability and growth are important research targets because there is awareness, especially by the authors, that there are still many important effects not currently in the present model described in this paper. Air-traffic-control (ATC) considerations, flight safety mechanisms, and the potential degradation in performance caused by overcapacity are three pertinent examples. In fact, a recent study by the National Research Council identified safety and ATC issues as serious concerns that imprint on the validity of the aforementioned SATS program.[10] Clearly, such constraints cannot be lightly disregarded.

However, the specification of constraints during the exploration phase, especially today's form of the constraints, can confine the outcome to solutions not very different (nor better) than at present. Thus, in full cognizance, the modeling described in this paper does not as yet consider safety and ATC constraints, but does contain the programming framework to allow for their incorporation after attractive regions of the unconstrained space are identified. Further, then, the nature of the imposed constraints can also be creative and new, as long as the ultimate measure of safety remains paramount. The intention is that the solution space development consisting of vehicle concepts and ATC networks should be examined and explored in tandem. In this spirit the model developed and presented in this paper includes from the outset a flexible structure that allows for the addition of new causal influences in a rapid fashion. The genesis of this structure lies in the formation of a mental model of the mobility problem.

A system dynamics approach is employed to define the context of the research problem in terms of a mental model as a precursor to the math model construction. Systems dynamics is a methodology that enhances learning about complex systems through tools such as causal loop diagrams. Such diagrams depict the relationship between all of the elements in the prescribed model as well as information feedback.[11] The causal-loop diagram shown in Fig. 1 is one such example for the mobility problem, where the attractiveness of PAVs is examined in relation to other transportation issues that affect choice. The arrows shown in the diagram represent the direction of causal influence, and the polarities represent either a positive or negative influence (i.e., balancing or reinforcing feedback structures). An example of a balancing feedback is how an increase in the attractiveness of PAVs tends to increase the number of PAV users and the number of trips they make per day. That would increase the traffic volume and, because of the increased congestion and eventual overcapacity, the travel time would now increase, causing a reduction in the attractiveness of PAVs. On the other hand, a reinforcing feedback mechanism is exemplified by an increase in PAV attractiveness driving down the acquisition cost as a result of higher vehicle production, in turn increasing the attractiveness even further. The objective of constructing the causal loop diagram, then, is to guide the development of analytical models of the dynamics

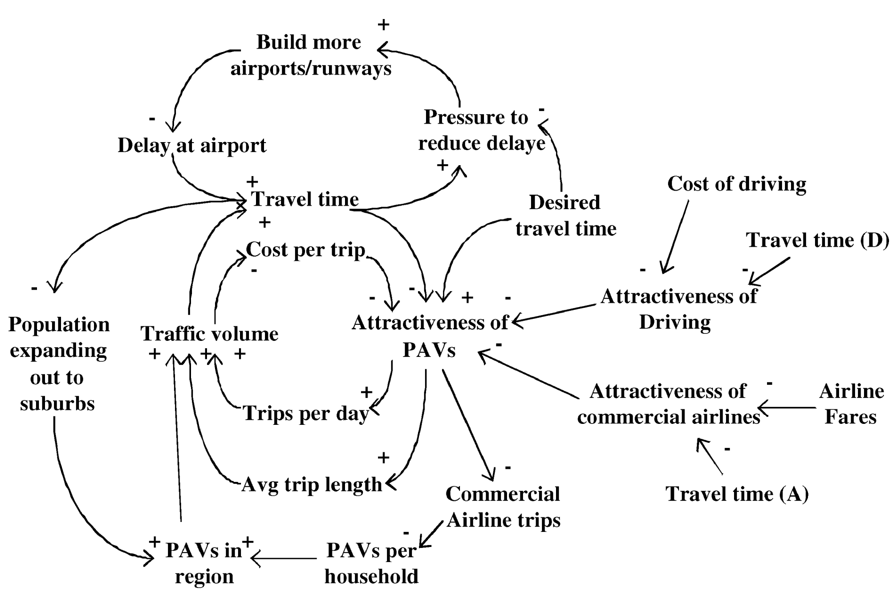

Fig. 1 Causal-loop diagram for the attractiveness of PAVs in a mobility context.

involved in reducing average travel times and improving the mobility of future travelers.

Elements of the causal-loop diagram are studied in more detail to derive particular metrics and mathematical relationships that comprise the mobility analysis reported in this paper. These metrics are later used as tradeable parameters, in search of vectors in the solution space that maximize the potential for increased mobility credit. Attractiveness is not just a metric measuring the consumer's psychological attraction to a vehicle concept, but rather the combined elements in the mobility credit. Different demographic consumer groups would make different vehicle choices based on their preferred mobility credit currency.

The remainder of this paper is focused upon a description of the analysis developed for mobility credit computation and examples of its use for exploring the solution space. In particular, a parametric design approach called the unified tradeoff environment (UTE) is employed, which facilitates the examination of the multidimensional interaction between system requirements, air-vehicle effectiveness, and infrastructure efficiency.

Technical Approach

The analysis developed is focused upon the computation of expressions of the mobility credit. A modular mission profile is established as a basis from which to calculate travel times. New concepts for establishing manifestations of the mobility credit are reported, including the adjusted cumulative cash flow that represents a net present value comparison amongst concepts. The primary purpose of the resulting analysis tool is to simulate the characteristics of an individual traveler's mobility credit and understand how that credit changes with alternative assumptions. To build the interrelated equation set, data from three main areas are needed: mission profile, vehicle performance/economics, and traveler profile. The data model is described first, followed by the mobility credit formulation.

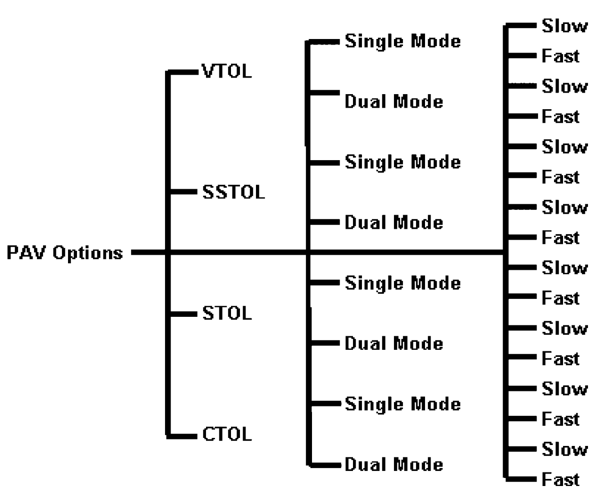

Fig. 2 Categorization of PAV options.

Data Definition

An interface is constructed to gather the required data for three profiles: mission profile, vehicle performance/economics, and traveler profile. Data in these profiles are used for the computation of 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 variety of simulation techniques. This feature is currently not active in the present model, but is an important function to be examined in subsequent research.

The mission profile interface allows users to select the desired vehicle options and mission options for analysis. PAV options have been categorized into four groups based on their takeoff and landing distances: vertical takeoff and landing (VTOL, 100 ft), extremely short takeoff and landing (ESTOL, 500 ft), short takeoff and landing (STOL, 1000 ft), and conventional takeoff and landing (CTOL, 3000 ft). Within each group is a second division for single or dual mode. Use of a single-mode PAV requires a separate ground vehicle such as a car or taxi to transport users to the PAV facilities. Dual-mode PAVs are those that operate as ground vehicles as well as air vehicles. Finally, each mode is then divided into two technology levels: fast and slow. Hence, there are a total of 16 PAV options, as shown in Fig. 2.

The generic mobility mission profile is depicted in Fig. 3. Each PAV option must complete the main mission from access portal A to access portal B. Access portals are assumed to be any facility that is capable of handling a PAV, ranging from a helipad, to private runways, to regional airports. The selection of a single-mode PAV is accompanied either by a personal car, rental car, or taxi to get to and from the access portal. Meanwhile, selection of a dual-mode PAV does not require an additional ground vehicle. Later computations require baseline travel choices; thus, the selection of a ground vehicle (personal car or rental car) or a commercial airline to complete

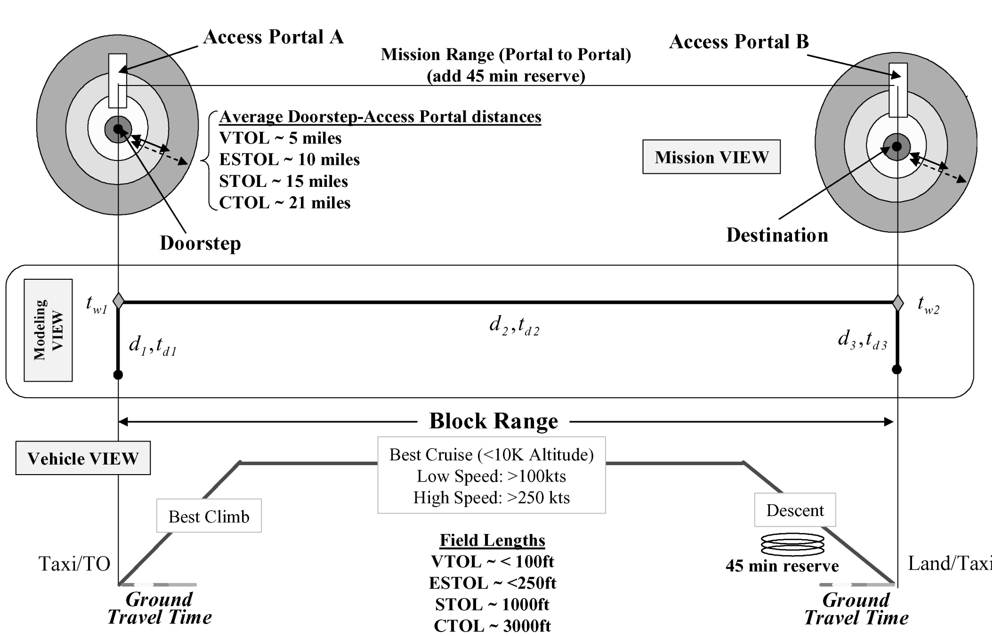

Fig. 3 Generic mobility mission profile.

Table 1 Mission, vehicle economics, and traveler profile inputs

Options	Selection
Mission	
Typical range (100–500 n.miles)	200 n.miles
Vehicle capacity (1–8 passengers)	2 passengers
Trips made per week (6–22 trips/week)	10 trips/week
Number of PAV-pooling passengers (max 4)	2 passengers
Vehicle economics	
Downpayment (as fraction of vehicle acq. cost)	25%
Loan interest rate (annual)	1%
Loan period	10 years
Predicted lifespan of vehicle (50 years max.)	30 years
User profile	
Current annual income	90,000 USD
Predicted income change per year in first 5 years	5.0%
Predicted income change per year in following 5 years	5.0%
Predicted income change per year in following 5 years	5.0%

Table 2 Population density and weather information

Code	Description
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
4	Urban population of 20,000 or more
5	Urban population of 2,500 to 19,999

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

the main mission is also modeled. In summary, the resulting tool can truly be considered a multimodal options analysis.

The next important interface is the traveler profile, which profiles the user's typical travel. The input options are shown in Table 1. The range for the typical distance of 100–500 n miles is selected based on the most commonly flown distance for general aviation aircraft, intercity driving trips, and regional commercial air travel.[12] Trips made per week refers to one-way trips made either to or from the workplace for the whole week. For instance, a typical five working days week constitutes 10 trips per week. The number of PAV-pooling passengers refers to the number of passengers onboard who share the direct operating cost of the PAV, similar to sharing gas cost in a car pool.

The final set of vehicle/mission profile options concerns the vehicle finance economics. The user is allowed to determine the specific vehicle financing terms, as shown in Table 1. Financing terms significantly influence the affordability of the PAV to a particular household. These financing options are downpayment for the PAV, loan interest rate, loan period, and predicted life span of the PAV. 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 a later section.

The current economic model is an individual purchase model, representing the full maturity of this new on-demand mobility concept. Other, more near-term models, such as fractional ownership and air taxi, are also currently 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 is based on the value-of-time-saved concept, which will be discussed later. As shown in Table 1, a user is allowed to input 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.

A fourth profile, only partially utilized at this stage, is the location profile interface. This profile 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 the rural-urban continuum codes[13] provided by the Economic Research Service of the U.S. Department of Agriculture. Meanwhile, weather is categorized into six weather group regions in the U.S based on a General Aviation Airport Availability Study[14] conducted by the NASA Office of Safety and Mission Assurance. 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). This information is summarized in Table 2.

Mobility Credit Computations

Two expressions are developed for the mobility credit concept introduced earlier: doorstep-to-destination time ($D - D_{\text{Time}}$) and adjusted cumulative cash flow (ACCF). In both cases the air-vehicle performance is characterized by parameters such as vehicle cruise speed, empty weight, fuel weight, mode (single or dual), and field length. An extensive vehicle database has been built to catalog the vehicle data.

Doorstep-to-Destination Time

Doorstep-to-destination time is the total travel time needed to get from the doorstep of the origin location to the final destination point. It is based on the generic mission profile in Fig. 3 and consists of times for the three travel legs and delays at the portal nodes. The expression for the $D - D_{\text{Time}}$ is shown in Eq. (1). For convenience in later studies, the two portal wait times are represented by the wait time at portal (TWAIT) parameter.

$$D - D_{\text{Time}} = t_{dl} + t_{wl} + t_{d2} + t_{w2} + t_{d3}$$

where

$$t_{d1} = \text{Travel Time}_{\text{Doorstep to Portal A}} = d_1/V_G$$

$$t_{w1} = \text{Wait Time}_{\text{Portal A}} = \text{TWAIT}$$

$$t_{d2} = \text{Travel Time}_{\text{Portal A to Portal B}} = d_2/V$$

$$t_{w2} = \text{Wait Time}_{\text{Portal B}} = 0.5^{*}\text{TWAIT}$$

$$t_{d3} = \text{Travel Time}_{\text{Portal B to Destination}} = d_3/V_G \tag{1}$$

The PAV options for field length categories (VTOL, ESTOL, STOL, and CTOL) have specific average distances from doorstep and destination to portals of 5, 10, 15, and 21 miles, respectively. These represent the mean separation distances between all four categories of airports around the United States and are based on the baseline SATS scenario attributes. Also, because of likely environmental and regulatory concerns particularly regarding noise and emissions it is assumed that dual-mode PAVs will not be allowed to operate in air mode directly from a populated residential or business location. As for the baseline modes, the average distance to a commercial airport is assumed to be 30 miles, and the wait time for commercial airline option is fixed at 2 hours for departures and 1 hour after arrivals. Meanwhile, the average block speed to/from access portals for personal automobiles and rental car/taxis are specified as 65 and 50 mph, respectively, simply because rental car and taxis require a time delay in acquiring these transportation services. The ground speeds of dual-mode PAVs are extracted from the vehicle database. All of the parameters mentioned throughout this paper can be modified and elevated to the level required for tradeoff studies to ensure that both reality and fidelity are maintained.

A parameter of interest that is related to the $D - D_{\text{Time}}$ is the trip block speed, given in Eq. (2). The block speed would be relevant as comparisons between missions of differing overall ranges are studied.

$$V_{\text{BLOCK}} = \frac{d_1 + d_2 + d_3}{D - D_{\text{Time}}} \tag{2}$$

Economic Computations—Adjusted Cumulative Cash Flow

One representation of the mobility credit is that of economic benefit, and this benefit can be captured through a modified 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 can 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 (additional references are readily available[15,16]) as follows:

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

2) *Cumulative cash flow* is the accumulation of cash flows since the beginning of the project/investment to any specified time and then to the termination of the project/investment; cumulative cash flow is the ordinate of the cash-flow analysis graph.

3) *Break-even point* is the first point in time when cumulative receipts exactly equal cumulative expenditures; the value of cumulative cash flow at that instance of time is zero.

4) *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.

5) *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.

6) *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.

7) *Payback period* refers to the period when the sunk cost is gradually paid back by excessive cumulative receipts; it is the time from capital investment to the break-even point.

8) *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.

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

Similar to any other business project or investment, the economic viability of a PAV concept can be depicted using a cash-flow analysis, which is computed based on the vehicle's performance. First and foremost, all cash flows are discounted to present value based on real interest rate, which includes the effects of inflation. Values for estimated annual inflation rate and annual nominal interest rate are specified to compute the annual real interest rate as follows:

$$r_0 = (r - f)/(1 + f) \tag{3}$$

The forms of expenditures for the cash-flow analysis are vehicle financing (interest and installment) and direct operating cost. Indirect operating cost is not included, under the assumption that it is insignificant compared to other costs. The direct operating cost comprises fuel, insurance, taxes, maintenance, aircraft-related overhauls, and the cost of acquiring piloting skills and license. 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. At the end of vehicle lifespan, a fixed salvage value of 15% of the initial vehicle acquisition price is assumed.

There are two baseline transportation modes: the personal automobile and the commercial airline. For travel distances from 100 to 500 n miles, an optimum baseline is selected on the basis of shortest travel time and lowest travel costs such that the comparisons between baselines and PAV options are most accurate. Optimal travel time for distances from 100 to 300 n miles is by car and for distances greater than 300 n miles is by commercial airline, as shown in Fig. 4. This observation is reinforced by data in Table 3, showing that the less expensive traveling mode for distances from 100 to 300 n miles is by car and for distances greater than 300 n miles is by commercial airline. Inevitably, the actual travel behavior is influenced by factors in addition to travel time and cost. Using a more detailed analysis of travel behavior, the optimal baseline can be selected through a probability distribution.

Table 3 Travel cost comparison for baseline modes

Travel distance, n miles	Cost difference relative to car, \$	Optimal baseline option
100	+166.79	car
200	+76.22	car
300	+36.12	car
400	−3.52	plane
500	−42.69	plane

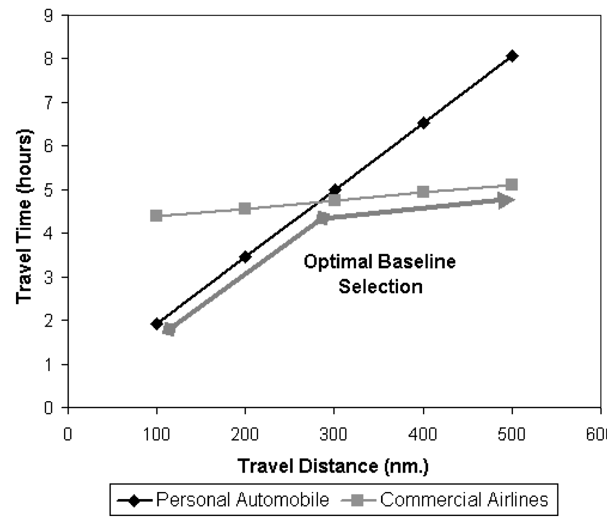

Fig. 4 Travel time analysis for baseline modes.

In terms of the actual costs of the baseline transportation modes, the cost of utilizing personal automobiles is rated at \$0.35 per statute mile of travel.[17] This mileage rate accounts for gasoline, oil, repairs, tires, insurance, infrastructural taxes, as well as depreciation. The cost of utilizing commercial airlines is computed from a quadratic polynomial fit of an array of current air ticket price list. 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.[18,19]

The cash-flow analysis is for a single vehicle owner who benefits from a pooling passenger through sharing of direct operating costs. In this paper there is one additional pooling passenger assumed, as shown in Table 1. There are two versions of cumulative cash-flow analysis; direct cumulative cash flow and ACCF. Direct cumulative cash flow is computed using data from the vehicle database for both PAV options and baseline options. The direct cumulative cash flow of PAV options can show either a net profit or net loss relative to the baseline cash flow, indicating a profitable or unprofitable PAV option as indicated in Fig. 5. The ACCF 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 caused by the adoption of a PAV concept [see Eq. (4) and Fig. 6]. An adjusted break-even point occurs when the PAV option breaks even with the baseline cash flow in Fig. 5 and is equivalent to the conventional break-even with the abscissa in Fig. 6.

$$\text{ACCF} = \text{PAV OptionCum.Cash Flow} - \text{BaselineCum.Cash Flow} \tag{4}$$

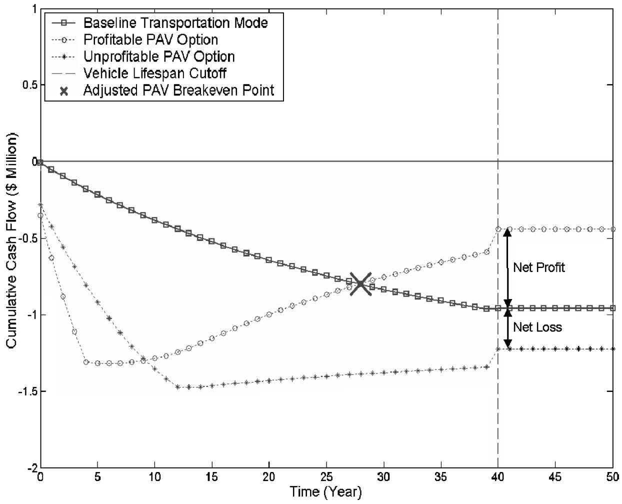

Fig. 5 Direct cumulative cash flows.

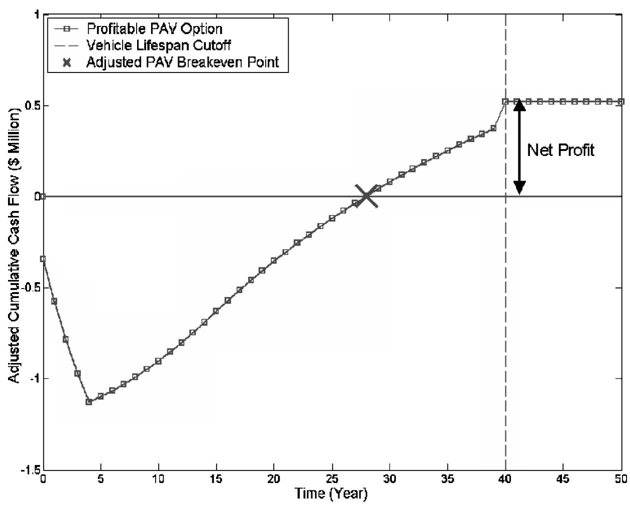

Fig. 6 Adjusted cumulative cash flow.

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 because one's worth of time truly depends on his or her personal outlook. Nevertheless, a reasonable assumption is 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 as shown in Eq. (5). For example, the value of time for an individual making $52,000 a year would be $25 per hour.

$$\text{Value of Time (\$/hr)} = \frac{\text{Annual Income}}{\text{2080 working hours per year}} \qquad (5)$$

Given a PAV option and a selected baseline option, the $D - D_{\text{Time}}$ can be computed using Eq. (1) along with the relevant assumptions and data from the vehicle database. Using these travel times of the baseline and the PAV, a metric named vehicle time saving index (VTSI) is created:

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; in this case the VTSI would take 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

$$\text{Value of Time Saved (\$)} = \text{VTSI* Hours of Utilization* Hourly Value of Time} \qquad (7)$$

With the economic assumptions and value of time concept just described, the cumulative cash flows for PAV concepts are computed as shown in the descriptive set shown Eq. (8):

$$\begin{aligned}
\text{Cumulative Cash flow} &= \text{Cumulative Profits} - \text{Cumulative Costs}\\
&= [\text{VTSY} + \text{Cumulated Profits}] - [\text{TCPY} + \text{Cumulated Costs}]
\end{aligned}$$

where

$$\begin{aligned}
\text{VTSY} &= \text{Value of Time Saved per Year for current year}\\
&= \left(\frac{\text{Value of Time}}{\text{1 hour}}\right) * \left(\frac{\text{Hours Saved by using PAV per year}}{\text{1 year}}\right)\\
&= \left(\frac{\text{Income Fluctuation Rate*Annual Income}}{\text{2080 working hours per year}}\right)\\
&* \left(\text{Hours Saved per day}^* \frac{\text{260 working days}}{\text{1 year}}\right)\\
\text{TCPY} &= \text{Total Cost Per Year}\\
&= \text{Annual Capital Payment}\\
&+ \text{Adjusted Annual Direct Operating Cost (DOC)}\\
&= (\text{Annual Interest Payment} + \text{Annual Installment})\\
&+ \text{Adjusted Annual DOC}\\
&= \Bigg[\text{Loan Interest Rate}^*\text{Loan Balance)}\\
&+ \frac{\text{Post Downpayment Balance}}{\text{Loan Period } n} \text{for } n \text{ years}\Bigg]\\
&+ \Bigg[\text{Real Interest Rate}^* \frac{\text{DOC}}{\text{1 hour}} * \frac{\text{Hours}}{\text{1 Trip}}\\
&* \frac{\text{Number of Trips}}{\text{1 week}} * \frac{\text{52 weeks}}{\text{1 year}}\Bigg] \qquad (8)
\end{aligned}$$

Implementation Studies

Unified Tradeoff Environment

The UTE[20] is a parameterized encapsulation of the integrated set of equations that comprise the mobility credit analysis. The mission, vehicle, traveler, and economic equation sets are linked in a simulation environment and employed as the analysis engine to construct the UTE. Three distinct outcomes are gained through the UTE. First, relationships between vehicle performance and economic attributes

$$\text{VTSI} = \left(\begin{array}{ll}\dfrac{D - D\,\text{Time}_{\text{Baseline}} - D - D\,\text{Time}_{\text{PAV Option}}}{D - D\text{Time}_{\text{Pav Option}}}; & D - D\text{Time}_{\text{Baseline}} > D - D\text{Time}_{\text{PAV Option}}\\ 0 \quad \text{otherwise} & \end{array}\right) \qquad (6)$$

Table 4 UTE construction—model parameters, their ranges, and outcome metrics

Description	Symbol	Units	Lower	Baseline	Upper
Requirements					
Mission range	S	miles	100	300	500
Wait time at portal	TWAIT	hour	0.25	0.88	1.5
Vehicle air speed	V	mph	200	350	500
Acquisition cost	ACQ	\$	50,000	175,000	300,000
Direct operating cost/hr	DOC	\$/hr	15	68	120
Personal income	INC	\$	75,000	237,500	400,000
Utilization	UTIL	trips/week	6	14	22
Metrics					
Block speed	V_{BLOCK}	mph	——	——	——
Doorstep-destination time	$D - D_{\mathrm{TIME}}$	hour	——	——	——
Vehicle time saving index	VTSI	N/D	——	——	——
Adj. cumul. Cash flow: year 5	ACCF5	year	——	——	——
Adj. cumul. Cash flow: year 10	ACCF10	\$	——	——	——
Adj. cumul. Cash flow: year 20	ACCF20	\$	——	——	——
Adj. cumul. Cash flow: year 30	ACCF30	\$	——	——	——
Net profit	PROF	\$	——	——	——

as prescribed by the assumptions made can be validated. Second, quick and accurate determination of the vectors of mobility system requirements necessary to achieve profitability for a given segment of users is possible. Finally, through visualization of the solution space offered by the UTE regions of feasibility can be identified.A region of feasibility is considered more valuable than optimal point solutions, especially in the exploratory stages of design (often called preconceptual design).

UTE Construction

The response surface methodology[21] underpins the construction of the UTE for mobility concept exploration. The generation of response surface equations (RSEs) is accomplished by using the integrated analysis tool to sample a set of points with the solution space and fitting a model equation to this set. The set is derived using a standard experiment design that specifies the number of samples required to estimate the number of effects in the model. The model form chosen for the present analysis is a second-order polynomial as shown generically in Eq. (9). In this generic form R is a given system response, b_i are the linear regression coefficients, b_{ii} are the quadratic coefficients, b_{ij} are the cross-product coefficients, x are the factor variables, and k is the number of factor variables. The merits of this choice of model can be determined by the examination of numerous statistical tests.

$$R = b_0 + \sum_{i=1}^{K} b_i x_i + \sum_{i=1}^{k} b_{ii} x_i^2 + \sum_{i=1}^{k-1} \sum_{j=i+1}^{k} b_{ij} x_i x_j \qquad (9)$$

A list of seven input factors (requirements) and eight responses (metrics) are identified for this sample construction of the UTE, as shown in Table 4. The input factors are selected to encompass vehicle (speed, cost), infrastructure (portal wait time), and traveler profile (income, utilization) considerations. The permitted ranges of variability are carefully selected to ensure that the requirement space exploration spans the conceivable combinations. Use of the environment beyond these ranges is not advised because this would indicate extrapolation of the RSEs beyond their validated domain.

With these seven input factors an experimental design that test factors at three levels (to estimate curvature in the second-order polynomial) is created resulting in a total of 79 simulation runs. The metrics of interest, shown in the bottom portion of Table 4, are recorded and used to generate the RSEs. A response that is of primary interest is the adjusted break-even year. However, because a significant number of cases might 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 years 5, 10, 20, and 30 are tracked to depict adjusted break-even point whenever cash flow becomes positive. With the

Table 5 R-Square validation data

Responses	R^2	RMSE	Response mean
VBLOCK	0.987485	9.101869	115.8972
TIME	0.999677	0.029326	2.914595
VTSI	0.986005	0.092352	0.386099
ACCF5	0.955347	226948.3	$-2.22E+05$
ACCF10	0.951098	471489.9	$-1.78E+05$
ACCF20	0.941972	1081283	648566.6
ACCF30	0.934911	1898640	2266191
PROF[a]	0.930181	2889517	4458849

[a]Net profit.

assumption that a fixed value of 40 years is used for vehicle life span, the net profit measures the cash flow at year 40. It can be either positive or negative, depending on whether the vehicle breaks even.

Once the simulations are completed and the data regressed, the predictive quality of the resulting RSEs must be validated. Two statistical measures are computed to examine the accuracy of fit. The adjusted R-Square value indicates how well the model fits the actual simulation data. An R-Square of one indicates perfect fit, but the more useful practice indicates that and R-Square above 0.9 indicates acceptable precision. R-Square data are provided in Table 5 and indicate acceptable levels for all responses. However, the R-Square does not measure the model's ability to predict points outside of the training set. A confirmation test is needed to test the predictive capability of the RSEs for points not in the training set. Thus, a confirmation test was also done for each response, with a typical result of a confirmation analysis for the adjusted cumulative cash flow (ACCF5) response reported in Fig. 7. The actual data are plotted on the ordinate and the predicted data on the abscissa. The horizontal dotted line is the response mean, and the dotted lines identify the 5% significance region. Because the mean line is not contained within the region between the two lines, the model is significant at the 5% level (i.e., 95% prediction confidence).

A primary purpose for constructing UTE is to visualize the sensitivities in the actual mobility analysis model and explore the solution space in real time. This is partially accomplished through depiction of the response surfaces via prediction profilers, which are displayed in Fig. 8. Prediction profilers are interactive response surface interfaces created within a statistical software package that allow users to track the dynamics of the parametric relationships in real time. A wealth of information is available and worthy of attention in these plots. Thus, a column-by-column insight is provided. However, because there are interaction terms in the model, as a particular factor is changed, all other sensitivities will change (perhaps even in sign) depending on the strength of the interaction.

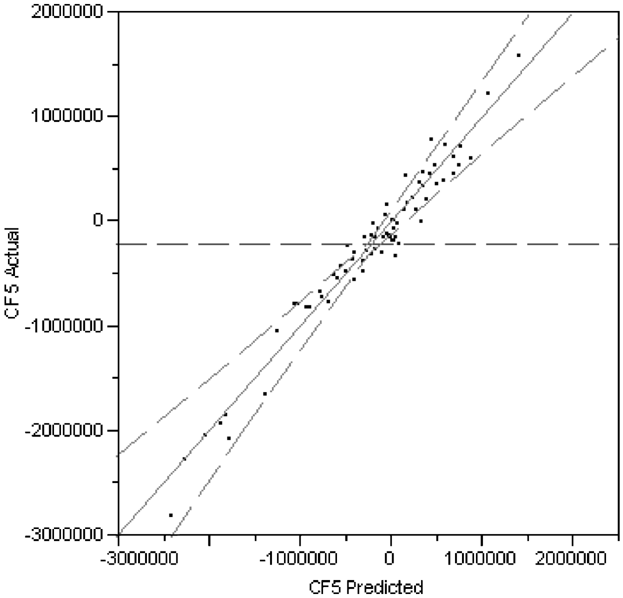

Fig. 7 Confirmation of predictive capability—ACCF5 response.

The most outstanding observation for the mission range input S is that a travel distance of 300 n miles appears to be the most favorable travel distance for PAV concepts in terms of ACCFs. For short distances the economic benefits of travel time savings by PAVs are not materialized, whereas for long distances the high cruise speed of commercial airliners overwhelms the significance of value of time saved by utilizing PAVs. The $D - D_{\mathrm{Time}}$ increases linearly with range as expected. Increases in portal wait time (TWAIT) result in moderate reductions in ACCF and significantly increase $D - D_{\mathrm{Time}}$ also. Income, utilization, vehicle acquisition cost, and DOC are all economic factors that do not affect travel times. Thus, flat lines for these columns on the VTSI, $D - D_{\mathrm{Time}}$, and VBLOCK are observed. However, they do impact the ACCFs in an expected fashion. Among these four, income and DOC have the largest impact on ACCF. Finally, the ACCFs are less sensitive to PAV cruise velocity V than DOC, an important insight that will be explored more fully in the following section. Improvement in vehicle cruise speed does have a significant positive impact on VTSI because it is the only factor that dictates the receipts in the cumulative cash flow. VTSI is also significant 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 Fig. 8.

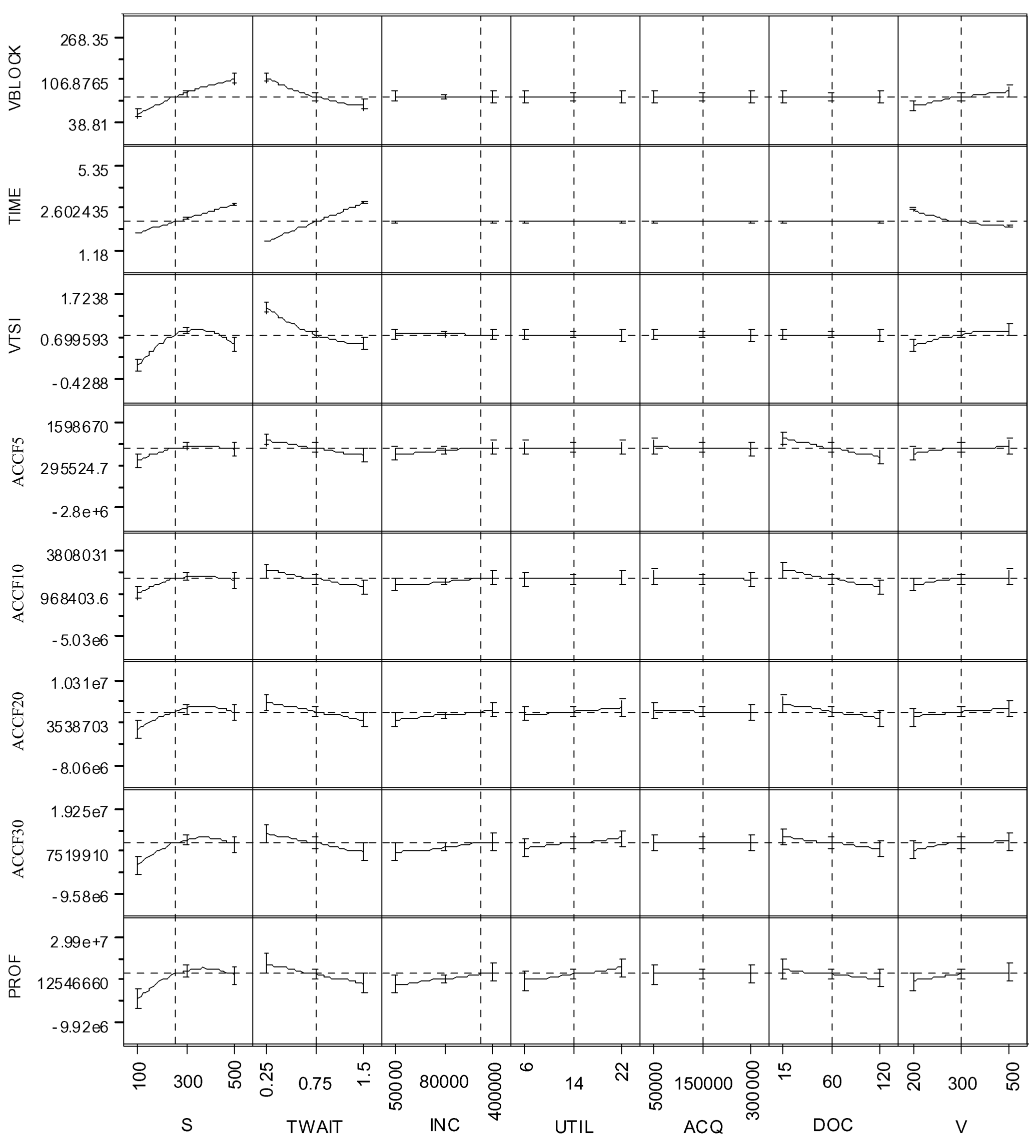

Fig. 8 UTE sensitivity results: prediction profilers on mobility credit metrics.

A pertinent question of interest is: What regions of the solution space are most promising with respect to desired improvements in mobility credit? To explore such a question, the UTE is employed in a manner similar to the traditional design carpet plots. To illustrate, three design parameters are examined: the vehicle cruise speed V, the portal wait time (TWAIT), and the vehicle direct operating cost (DOC). Each of the three represents a distinct element of the overall mobility system design, respectively impacting mobility credit by making travel faster in the air, faster on the ground, or cheaper overall. Together, these three form the solution vector shown in generic form in Eq. (10).

$$\text{soln} = [V \quad \text{TWAIT} \quad \text{DOC}] \tag{10}$$

A baseline traveler is defined, consisting of an individual who earns $50,000 per year and seeks to travel on average 400 n miles 12 times per week. The baseline system characteristics include a vehicle air cruise speed of 320 kn with a DOC of $70/hr and a portal wait time of 0.75 hours. It is desired to break even after five years, ACCF5 > 0. The solution space for this problem can be explored through an interactive carpet plot that is generated from the response equations. For example, the ACCF5-constrained, TWAIT-V space is represented in Fig. 9, indicating that the baseline system is infeasible (shaded region). Contours of constant $D - D_{\text{Time}}$ are also shown ranging from 2 to 3.75. This is not a static diagram, however, because real-time updates of the space can be produced through use of a user interface (not shown) that allows for the adjustment of any input parameter.

The situation in Fig. 9 clearly indicates that a speed improvement alone up to the maximum value allowed provides no solution. However, other solution vectors do exist. A reduction in DOC alone can bring about a solution (Fig. 10) as can an isolated reduction in TWAIT (Fig. 11). However, these two solution vectors would require significant technological advancements in the respective areas such as dramatic reductions in operation/maintenance cost or a dramatic improvement in infrastructure at the portals. Each of these solutions was foreshadowed by the magnitude of the slopes for ACCF5 found in Fig. 8.

Of course, a vector combination of all three factors is most interesting and can be found in the UTE, as illustrated in Fig. 12. Essentially, the closest feasible point is pursued, which would be optimal if the level of difficulty in each technology area improvement is equivalent. An optimal search in which the three technology areas have distinct levels of difficulties is also possible. For this case one could use a variety of multicriteria optimization approaches, such as those by developed Messac and Ismail-yahaya,[22] to avoid the difficulties associated with a simple weighted-sum approach. A summary of the solution vector search is shown in Table 6.

Many other scenarios can be generated from these prediction and contour profilers. These two tools present the solution space as a parameterized tradeoff environment that is visibly comprehensible and easily manipulated. This promotes intelligent decision making by allowing the user to quickly 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. This type of guidance is the important information needed by vehicle designers to maximize the probability of producing successful designs (and thus reducing

Table 6 Solution vector summary

Solution Scenario	Solution Vector [V TWAIT $DOC]
Baseline (infeasible)	[320 0.75 70]
V only	No solution
TWAIT only	[320 0.30 70]
$DOC only	[320 0.75 56]
All	[360 0.55 6.5]

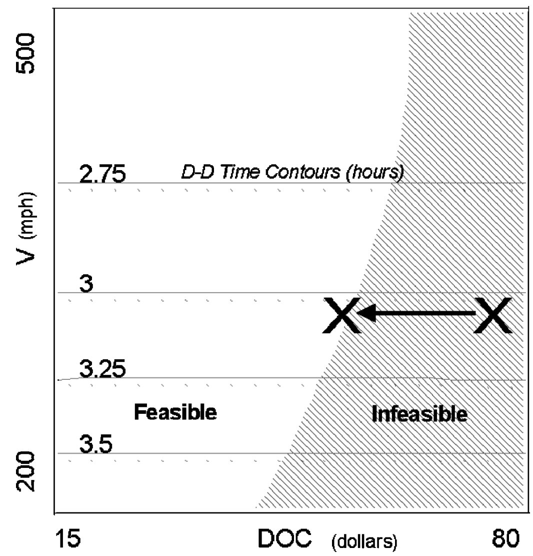

Fig. 10 Cruise velocity vs direct operating cost, constraint ACCF5 > 0 imposed.

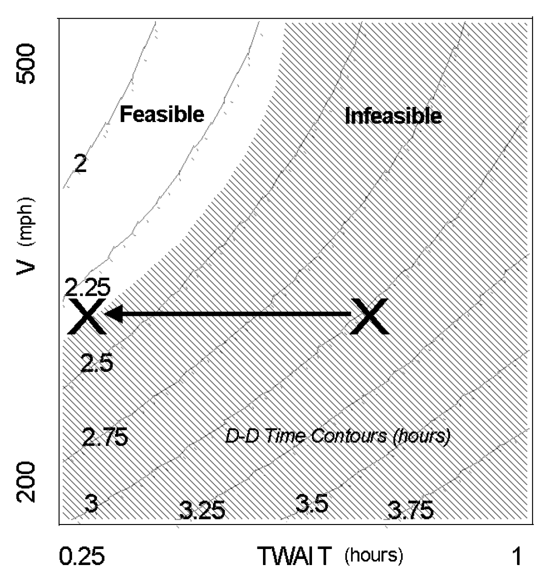

Fig. 11 Cruise velocity vs wait time, constraint ACCF5 > 0 imposed.

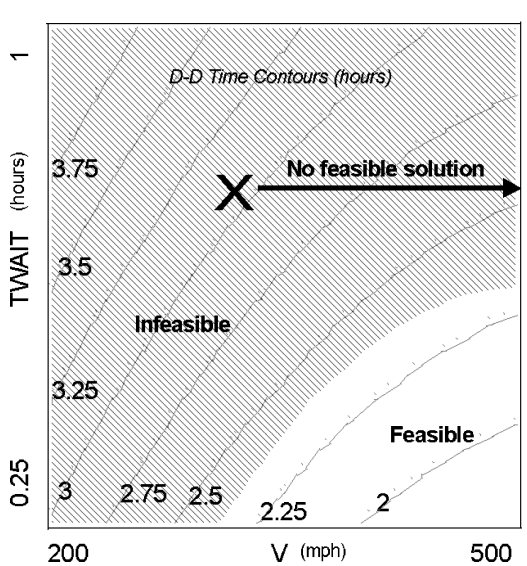

Fig. 9 Wait time vs cruise velocity, constraint ACCF5 > 0 imposed.

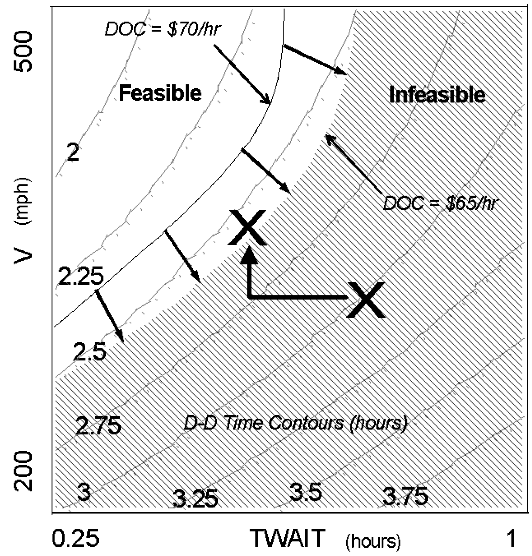

Fig. 12 Vector sum solution, constraint ACCF5 > 0 imposed.

wasted time, money, and creativity), hence leading to uncertainty assessments.

Quantification of uncertainty must play a major role in researching advanced air-vehicle concepts, technologies, and mobility markets years into the future. For example, one might wish to explore the impact of variability in the performance, cost, or operation of a particular concept on mobility credit. This is certainly a more realistic case, where, for example, travelers might have more or less income around a mean, a variable rate of utilization, etc.. The authors operate from a background that employs a direct modeling of uncertainty in a probabilistic fashion,[23] and there are numerous promising methodologies for the treatment of uncertainty in aerospace design.[24] The UTE is currently being employed in the performance of uncertainty studies to characterize the robustness of the good regions of the solution space to variations in the key metrics of cruise speed, direct operating cost, and wait time.

PAV Concept Analysis Environment

In addition to enabling the solution space exploration, the mobility credit analysis also supports the direct comparison of radically different individual vehicle concepts. Heretofore, it has been difficult to fairly judge the value of VTOL (with a low cruise speed), for example, vs the value of CTOL (with high cruise speed) on the basis of mobility metrics. Thus, the primary objective of this section of the paper is to demonstrate the ability to compare potential PAV options in terms of technical, economical, and operational values. The comparison metric is the net present value of utilizing the PAV option relative to the baseline transportation mode, computed through the adjusted cumulative cash-flow analysis. Subsequent to the comparison, a gap analysis can be performed to identify required technology infusions.

Baseline vehicles for four out of the 16 PAV options presented in Fig. 2 have sufficient data available for investigation. These four are single mode and represent a mix of current production vehicles and advance technology prototypes. For example, a single-mode, slow-class VTOL would be commensurate with the Robinson R-44 helicopter, the ESTOL single mode would be indicative of the CarterCopter Gyroplane[4] prototype, and the single-mode fast and slow CTOL would be representative of the Eclipse Aviation Eclipse 500 Jet and the Lancair Columbia 300, respectively. For illustrative purposes only the household income and travel distance parameters are selected for sensitivity analysis while all others are kept fixed. Household income is varied for two values, $200,000 and $350,000, while travel distance ranges from 100–500 n miles. These are realistic values based on tradeoffs between performance and costs of current technology level vehicles.

Table 7 Mission and economic assumptions for PAV concept comparison study

Options and variables	Values
Mission	
Trips made per week (6–22)	14 trips/week
Number of PAV pooling passengers (max 4)	2 passengers
Vehicle economics	
Downpayment (as % of vehicle acq. cost)	15.0%
Loan interest rate (annual)	9.0%
Use recommended loan period? (*y* or loan period)	*y*
Loan period	12 years
Predicted life span of vehicle (50 years max.)	40 years
User's economic	
Predicted income change per year in first 5 years	5.0%
Predicted income change per year in next 5 years	5.0%
Predicted income change per year in next 5 years	5.0%
Other economic	
Annual % allocation of income for transportation	15.0%
Annual inflation rate	3.7%
Annual nominal interest rate	7.0%
Annual real interest rate	3.2%

Table 8 NPV for vehicles for two income levels

Options	100 n miles	200 n miles	300 n miles	400 n miles	500 n miles
40-year net present value at an income of $200,000 ($ million)					
VTOL, slow	−2.038	−1.094	0.263	−2.662	−4.055
ESTOL, fast	−4.882	−2.702	0.599	0.381	−0.988
CTOL, slow	−2.513	−0.995	1.509	−0.269	−1.674
CTOL, fast	−4.350	−0.895	2.560	1.733	1.280
40-year net present value at an income of $350,000 ($ million)					
VTOL, slow	−1.968	−0.008	2.674	−2.098	−3.984
ESTOL, fast	−4.037	−3.164	0.451	−3.387	−6.070
CTOL, slow	−2.050	0.786	5.346	2.453	0.418
CTOL, fast	−3.712	2.295	8.301	6.855	6.266

Assumed values for the mission and economics assumptions are as in Table 7.

The net present values (NPV) of utilizing these four potential PAV options at the end of vehicle life span are obtained using the methods presented earlier. Three observations can be made from the results, which are shown in Table 8. First, those options that break even most often can be determined, indicated by a positive NPV. Overall, the CTOL, fast concept breaks even in six of eight cases, whereas the VTOL slow does so in only two of eight. Second, the finding that 300 n miles is the most appropriate travel distance for any PAV option is confirmed, supporting the earlier result. For short distances, the economic benefits of travel time savings by PAVs over auto are simply not materialized.

Meanwhile, for long distances, the block speed of commercial airlines outweighs the time-delay penalty at airports such that value of time saved by PAV becomes less significant. Finally, within a mission distance bin, the option closest to profitability can be selected. For example, if one desired to focus upon the 100 n miles distance, the VTOL, slow option is preferable (though still not profitable). Shortcomings in speed and operating cost need to be addressed. A sensitivity analysis is performed to determine the optimal mix of improvements, now that vehicle cruise speed and cost are identified as two areas that require technology infusion for the VTOL concepts. The results of this analysis are presented in Fig. 13.

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 DOC. The assumptions made are similar to those given in Table 7 and based on a $200,000 annual household income level.

Two main observations are made based on the technology sensitivity analysis. First, for a short-distance trip (100 n miles) reduction in DOC yields the greatest increase in net profit, whereas for a long-distance trip (500 n miles) an increase in cruise speed yields the

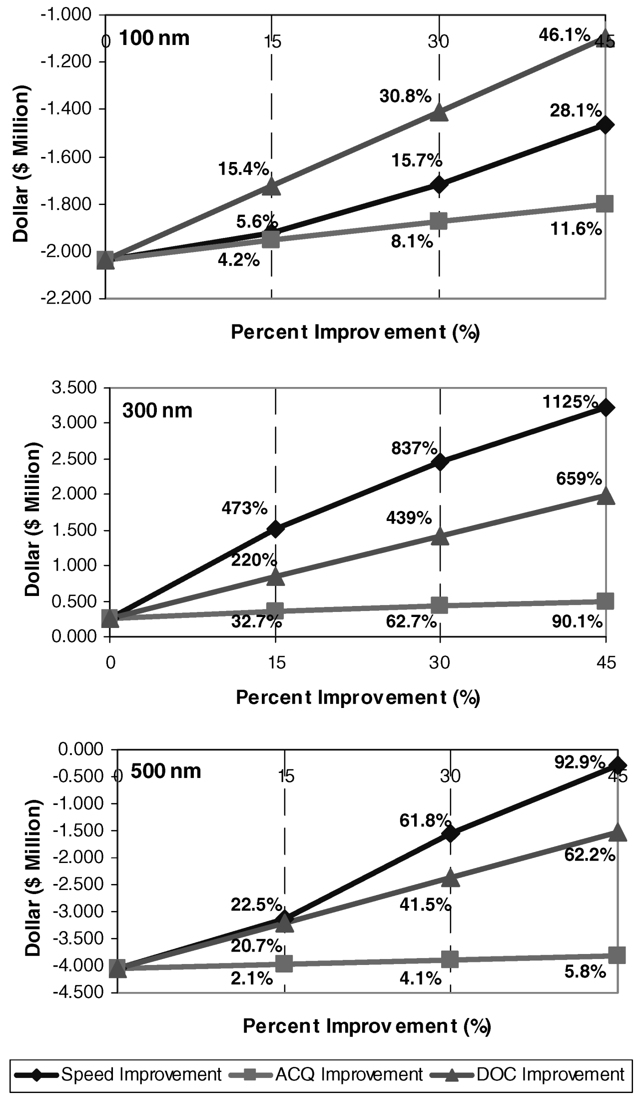

Fig. 13 Net profit of VTOL, slow concept in year 40 with varying complexity factors.

greatest increase in net profit. The vehicle speed improvement will not significantly benefit the viability of the PAV option for short-distance traveling because the air-leg travel time is small compared to the ground-leg travel time. Subsequently, a reduction in DOC becomes the more pronounced factor in improving viability. Second, 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 a new generation of VTOL PAVs can be pursued in a manner that maximizes the potential for success.

The design guidance afforded by a mobility credit analysis is important because there is a clear recognition that major advancements in technology are needed to make PAVs affordable for a 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 current research.

Conclusions

The concept of a mobility credit was introduced in this paper. The mobility credit is a multielement objective that represents the ability to improve an individual's mobility through travel time savings, travel cost reductions, travel flexibility enhancements, or combinations of the three. Mobility credit was found to provide a useful characterization of the solution space for future on-demand transportation architectures. A mathematical model of mobility credit was constructed through an integration of transportation option, vehicle performance, and life-cycle economic analyses. Doorstep-to-destination time and net present value were two realizations of the mobility credit. The model was then combined with parametric methods to create a unified tradeoff environment for the examination of future mobility systems. The tradeoff environment was employed to identify promising regions of the solution space and the sensitivity of those regions to model assumptions. Paths to the promising regions were represented as vectors of requirements that are meaningful to vehicle and infrastructure designers. In addition, radically different individual vehicle variants were assessed against each other on a fair basis through the elements of the mobility credit.

Within the parameter space explored, initial findings indicate that significant improvement in vehicle speeds, operating costs, and acquisition cost will be required before such on-demand air vehicles could be considered affordable means for improving the mobility credit for self-operated PAVs. A particularly important finding is that, over the long term, improvements in a vehicle's direct operating cost are preferable to improvements in cruise velocity. Further, the ability to minimize delays for mode transfer has a great impact on mobility credit as well. A combination of improved system efficiency and reduced vehicle operating costs, then, can result in only moderate cruise speed improvements being required.

Current work is proceeding to embed the mobility credit model into a larger transportation system analysis approach, including external feedback that will cause the attractiveness of the concepts to shift over time and business models other than personal ownership. The long-term objective for this research is to provide a living system study that has the flexibility for frequent (and perhaps previously unimagined) updates.

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