Integrated Model for Studying Small Aircraft Transportation System

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A systems engineering methodology was used to study the National Aeronautics and Space Administration's (NASA's) Small Aircraft Transportation System (SATS) concept as a feasible mode of transportation. The proposed approach employs a multistep intercity transportation planning process executed inside a Systems Dynamics model. Doing so permits a better understanding of SATS impacts to society over time. The approach is viewed as an extension to traditional intercity transport models through the introduction of explicit demand–supply causal links of the proposed SATS over the complete life cycle of the program. The modeling framework discussed is currently being used by the Virginia SATS Alliance to quantify possible impacts of the SATS program for NASA's Langley Research Center. There is discussion of some of the modeling efforts carried out so far and of some of the transportation modeling challenges facing the SATS program ahead.

Barring the effects of September 11, 2001, and the Persian Gulf War in 1991, the demand for air transportation services has followed a positive upward trend in the United States from the 1980s to 2001. According to FAA statistics, air carrier and regional commuter operations grew 4.1% from 1992 to 1998 (*1*). Some large airports like Hartsfield International in Atlanta, Georgia, handled more than 900,000 aircraft operations and 37 million enplanements in the year 2000. The percentage of passengers enplaned at the top 50 airports increased from 77% in 1989 to 83% in 1999 (*2*), indicating further consolidation of the airline hub-and-spoke system. There are significant indications that the capacity of the National Airspace System (NAS) is reaching a plateau owing to limited airport and airspace capacities. A natural effect of the NAS capacity constraints on travel is increased travel times for random origin–destination (O-D) pairs due to circuitous routing caused by the mature hub-and-spoke air transportation network. These trends promote travel inefficiencies (as measured by door-to-destination travel times) that have prompted the National Aeronautics and Space Administration (NASA) to examine new aeronautical technologies to reverse the pattern. One proposed set of technologies is the Small Aircraft Transportation System (SATS). According to NASA, the SATS promises affordable air transportation to the public, using inexpensive all-weather aircraft—privately owned, rental, air taxi, or some form of fractional ownership.

The SATS is a spin-off of the aeronautical engineering advances made by NASA and industry in the past 6 years. NASA created the Advanced General Aviation Technology Experiment (AGATE) program to improve the aerodynamic and systems design features of light aircraft and to study new manufacturing methods for General Aviation (GA) aircraft. The General Aviation Propulsion program developed propulsion technologies to complement the products of AGATE. One of the arguments supporting the SATS concept is the potential use of several thousand public airports without commercial revenue service in the United States. If the affordability and safety-related technology challenges are resolved, this form of transportation could allow access to many rural and urban communities alike. It is important to recognize that the SATS is a concept that faces numerous challenges, including mode affordability, environmental and energy impacts, airport infrastructure, air traffic integration, societal acceptance, human factors, flight safety, and so forth. Nevertheless, it is interesting to remember that many of the same challenges burdened the development of the automobile 100 years ago.

The most pressing research need for novel transportation concepts like the SATS is the development of a coherent system architecture definition, including the potential end state for the system, and a systems engineering approach to prove that the concept works. This paper describes an integrated approach to study the SATS that is a first iteration to achieve this goal.

SYSTEMS ENGINEERING APPROACH TO STUDY SATS

System engineering methodologies have been developed and implemented in the analysis of large-scale systems over the past 5 decades (*3*). These methodologies are commonly used in defense and aerospace programs and in technology-based systems, such as computers and communications systems. Intercity transportation systems such as the SATS involve many of the same challenges, to reach acceptable planning and design solutions. The initial step common to the initiation of major new systems is the development of a system architecture. A system architecture is the framework that describes how the system components are interfaced and work together to achieve total system goals. It describes the operation of the system, what each component of the system does, and what information is exchanged among the components.

Systems Engineering Viewpoint

Any transportation system intended to serve society through the 21st century and beyond must address a hierarchy of goals and issues ranging from the strategic (sustainable development) to the tactical (the concept of operations), and it must include interfacing with the existing transportation system. In many past studies, transportation planning, policy, investment, and operating decisions for one mode have been made in isolation from those in other modes—incomplete inputs from a broad base of disciplines. An integrated approach is thus

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needed to promote the best informed decisions governing planning and management, and to provide a realistic framework for allocating public- and private-sector efforts. At the same time, new transportation modeling approaches are needed to frame and test new transportation paradigms such as the SATS, and to provide a strategic vision for rallying public and government support.

Traditional transportation economic analysis to determine feasibility is concerned with problems assumed to occur in a single time period ranging from a year to a few decades. This sort of static analysis is inadequate for analyzing long-term sustainable development systems. In designing a sustainable society, events that are usually related through more than one period of time must be considered. This transition from static to dynamic analysis involves more than just adding individual static time periods. It requires an explicit representation of transportation demand-and-supply functions over the complete life cycle of the transportation system. A body of dynamic behavior and principles of structure has existed for decades, which allows us to organize and understand the development process of a region or a whole nation—a process affected by feedback in that it features the synthesis of demand and supply functions. The Systems Dynamics (SD) methodology proposed by Forrester (*4*) offers a way to analyze large-scale sociotechnological systems. A causal diagram depicts the relation, in the form of information flows, among decision policies, rate, level, and other variables. A policy is an independent variable defining the action of a decision maker. A rate variable describes the flow of information from one area to another. A level variable represents an accumulation of the information that varies over time. A simple SD causal diagram is shown in Figure 1. The model presented in Figure 1 is a very simple one and serves only to illustrate the approach taken in the SD. The model presents the classical behavior of many transportation systems (including intercity transport systems) over time. Three feedback loop structures in the system (labeled I, II, and III) can be identified in Figure 1—two positive loops (I and III) and one negative one (II). The negative feedback loop limits the growth of the system as a result of inherent limits in the capacity of the system and the corresponding deterioration of transportation level of service (LOS). The typical behavior of this first order feedback system is a logistic curve (i.e., negative feedback with coupled first order loops around the state variable, demand for SATS services). Although the model presented in Figure 1 lacks apparent spatial relationships (corridor or network attributes), these relationships can be incorporated using standard spatial analysis tools such as a geographic information system, coupled with a computational engine, to solve the basic differential equations that drive the system behavior over time.

SATS TRANSPORTATION SYSTEMS MODEL

This section presents a systems engineering methodology to study the SATS concept as a feasible transportation system. The proposed approach models demand–supply causal links of the proposed SATS transportation system over the complete life cycle using continuous state variables. Traditional approaches in transportation planning characterize the behavior of the system at two discrete points in time, namely the initial state (baseline) and the horizon year (end state). The SATS concept, as proposed by NASA, could create a natural evolution in intercity travel if a series of social and technology factors are met over time. However, the time gap between the initial and end states is critical for the SATS, because there are many uncertainties in the development of this technology (e.g., cost, reliability, affordability, safety, and environmental concerns)

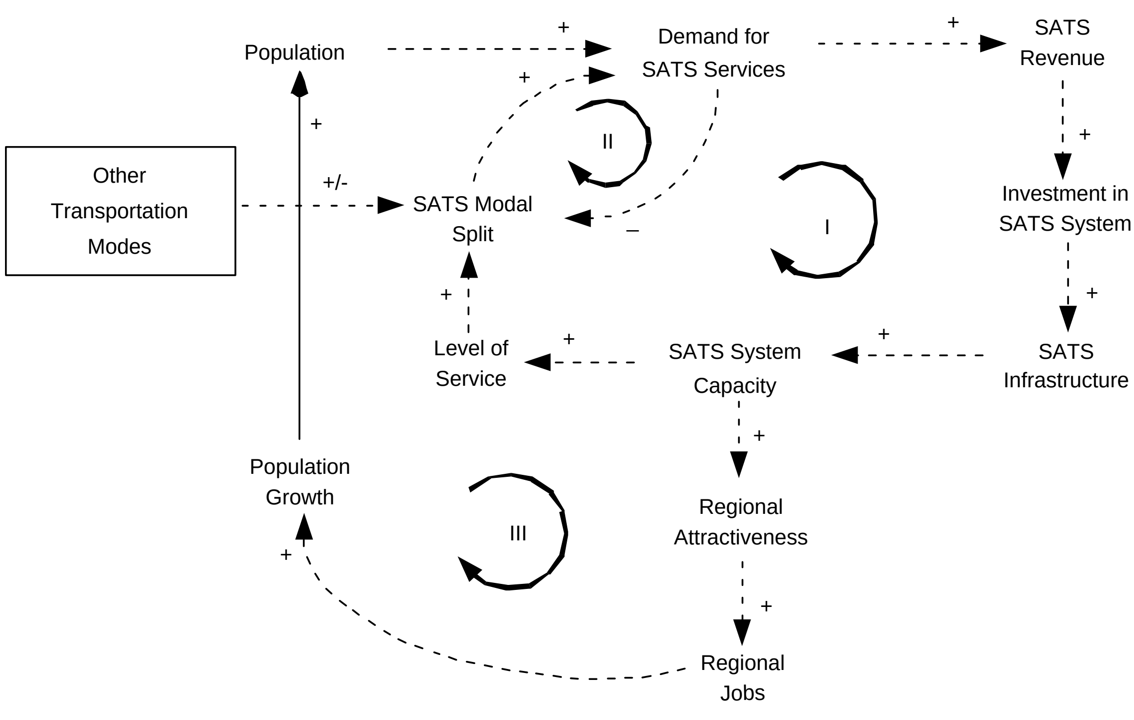


FIGURE 1 Simplified causal diagram to study the intercity demand function for the SATS.

and more so in the deployment strategy associated with such a system. Therefore, it is critical to model intermediate points in the life cycle of the SATS system and in the national decisions needed to foster a suitable implementation strategy. Our approach permits this modeling while preserving all of the qualities of traditional intercity multimodal analyses.

Modeling Approach

The proposed approach to study the deployment of the SATS, in the presence of other competing forms of transportation, including electronic commerce and information technologies, is shown in Figure 2. The proposed model relies on the SD methodology to assess the impact of transportation technologies in society at the national and regional levels. In this context, the SD is implemented as a continuous simulation model to be calibrated using historical data and employing SATS technology demonstration studies as technology demonstration results become available. Ultimately, the method proposed yields macroscopic measures of effectiveness, such as travel time benefits, noise impacts, fuel and energy usage, nonuser economic benefits, and air transportation system congestion and delays.

The diagram shown in Figure 2 includes several important proven feedback loop structures that are characteristic of existing transportation systems, and it shows their effect on the regional and national economy. The blocks depicted in Figure 2 have two implicit attributes: time dependencies and spatial dependencies. The first attribute refers to the time variations that naturally occur in a complex transportation system over time. For example, the evolution of the SATS demand function could be described as differential equations whose rate variables (rates of change) are generated by model influences such as production capacity, population, and perhaps other socioeconomic variables.

The second attribute of each block represented in Figure 2 is the spatial coverage of the variables presented in the model. For example, when performing a network analysis at the national level, one can characterize hub, reliever, and GA airports as part of a large, spatially distributed airport–airspace network. The elements of this network can be modeled using mathematical abstractions depending on the level of detail required. In some cases, an airport might be appropriately represented by the sink-source type node without information about runways, taxiways, and gates (i.e., mesoscopic and macroscopic analyses). In other cases, the airport would require refinements that include runways, taxiways, and individual gates with a detailed representation of the aircraft kinematics to achieve a desired level of model fidelity.

Figure 2 depicts the following critical steps to study the SATS transportation concept from a life-cycle point of view. These steps are:

- Inventory and scenario analysis,
- Intercity trip generation analysis (including all competing modes),
- Intercity trip distribution,
- Intercity modal split,
- Air transportation network analysis, and
- Air transportation system performance assessment.

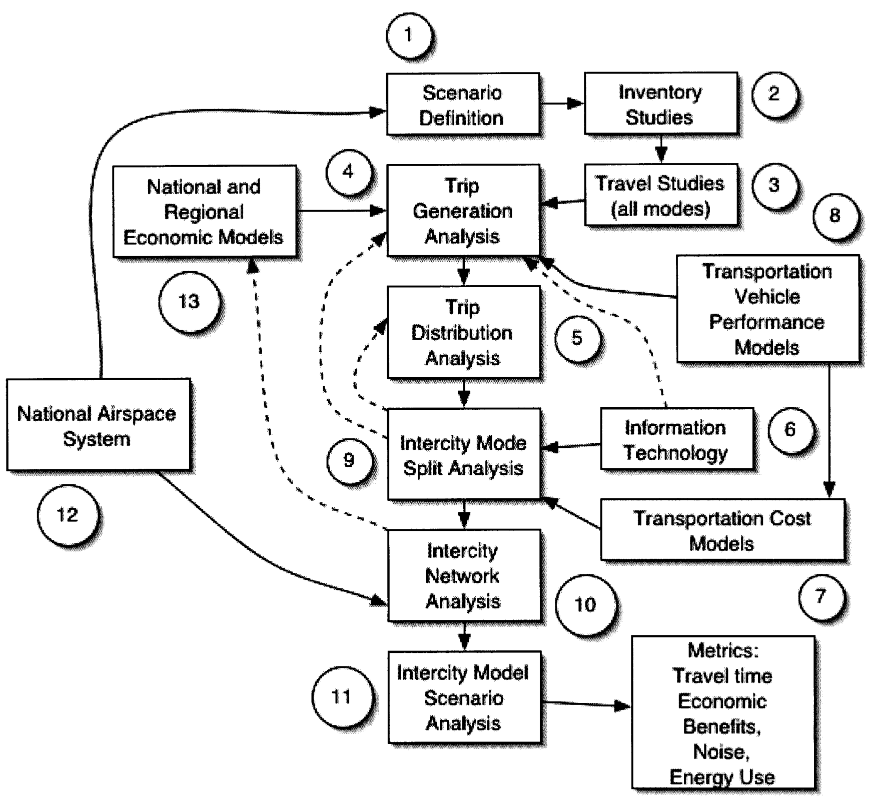


FIGURE 2 Generalized intercity transportation systems analysis methodology.

There are implicit connections between the blocks depicted in Figure 2 that make a life-cycle analysis process possible. For example, once an evaluation of airspace conflicts among SATS aircraft—or between SATS and their airline counterparts as shown in Block 10 in Figure 2—is performed, it will be necessary to adjust the intercity travel times assumed in the trip generation and trip distribution analyses (Blocks 4 and 5). When all the modeling blocks are completed, an equilibrium point is reached, to determine how many people travel on each mode and how many new flights are generated through the NAS. The process is then repeated for every time point in the life cycle. This process is shown graphically in Figure 3. At every time step in the execution of the model, all submodels represented in Figure 2 are executed, and state variables are carried out from one step to the next using standard numerical integration techniques. The model is driven by population and other socioeconomic characteristics considered exogenous to the model.

Relationship of Transportation Analysis and SATS Technical Capabilities

There are two intrinsic objectives in the SATS program: a tactical objective to develop four key technical capabilities, and a strategic objective to make SATS a feasible mode of transportation. The tactical goals are

- Improving lower landing minima;
- Allowing safe, high-volume operations at non-towered airports;
- Improving single pilot safety; and
- Allowing seamless integration in the en route airspace system.

The model discussed in this paper addresses the strategic objective of the SATS considering the effects of the tactical goals of the program. The relationship between the transportation system analysis methodology described in this paper and the four technical capabilities currently being studied in the SATS program is illustrated in Figure 4. Various NASA-sponsored SATS Alliances (including the Virginia SATS Alliance) are developing design and analysis tools to

- Predict human performance metrics,
- Provide safety improvements to the system in low visibility airport conditions and in the en route airspace system, and
- Enhance the ability to operate higher volumes of traffic at non-towered airports.

The human performance models feed three critical technical models:

1. SATS airport model;
2. SATS en route analysis model; and

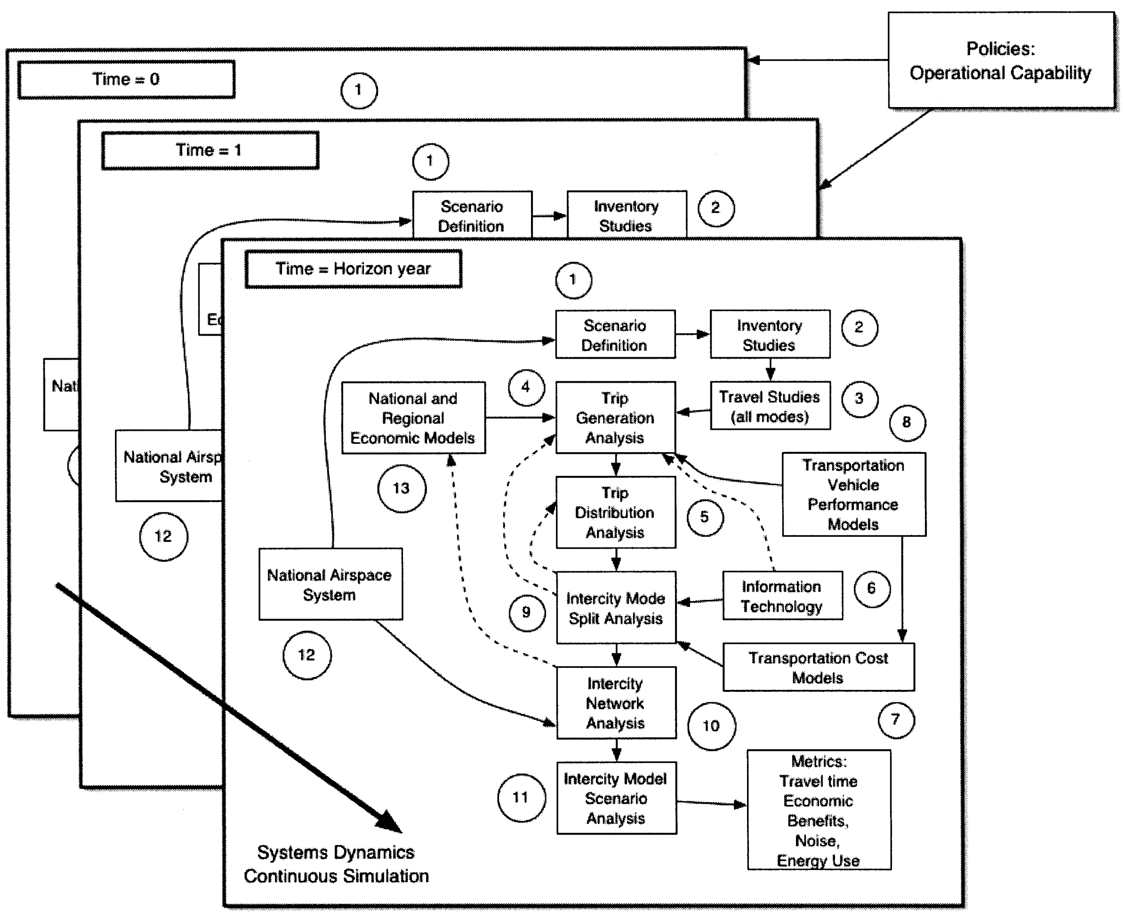


FIGURE 3 Transportation systems analysis implementation strategy.

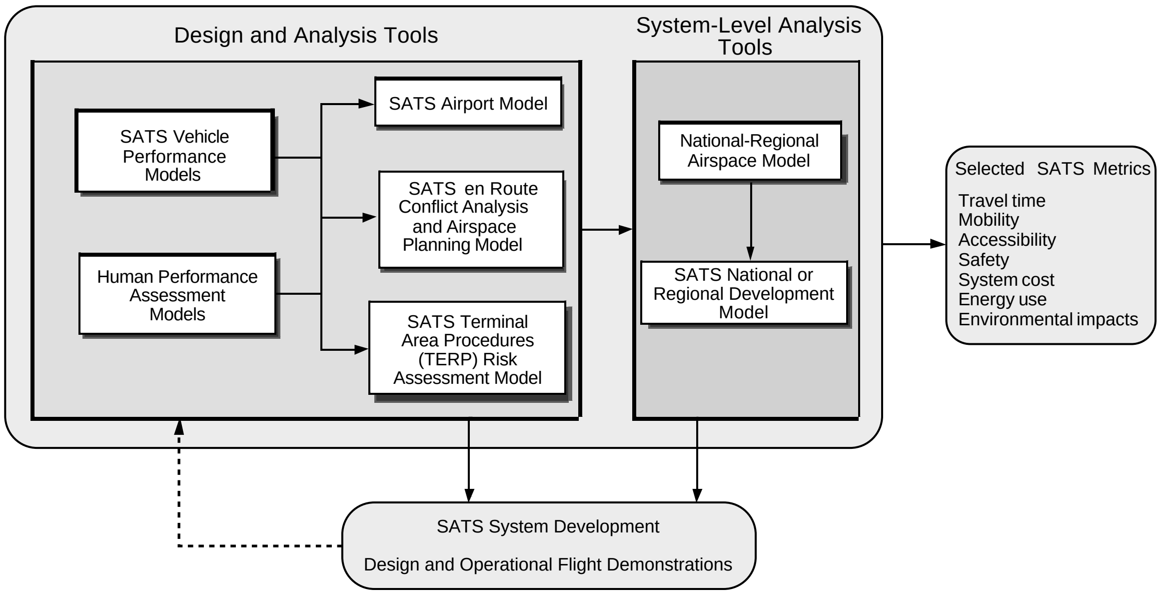


FIGURE 4 Relationship between transportation systems analysis and other analyses in the SATS program.

3. SATS Terminal Area Procedures model that produces airport and terminal area metrics such as the number of conflicts, delays at airports, and target level of safety among others, for every concept of operations investigated.

The outputs of these models feed the regional transportation analysis described in this paper.

To illustrate the point, consider the issues of improved low-landing minima capabilities and improved safety with single-pilot operations. In theory, the lower-landing minima capability could make the SATS mode more reliable and, in general, could increase its mode share (i.e., ridership). At the same time, enhanced operations at nontowered airports could expand the capacity of the NAS and improve opportunities for intercity travel across the country. All this assumes the mode is both available and affordable to a broader section of the U.S. population, an issue that can be studied in the proposed model once a calibrated mode split model is available. The real effects of these complex causal relationships need to be determined through analysis, simulation, and ultimately flight experiments.

On the demand side, the transportation system analysis described here provides an opportunity to measure the potential demand function that would result from reliable and safe SATS operations. This analysis includes multiple SATS ownership operations, including

- Full SATS aircraft owners,
- Fractional ownership,
- Air taxi services, and
- Airline-style scheduled operations using SATS.

All these submodes are factored into the intercity modal split analysis carried out in Block 9 of Figure 2. The modal split analysis is critical in the demand estimation for SATS services. In turn, the demand function influences the measures of effectiveness such as mobility, accessibility, safety, and capacity of the system, as shown in the lower right-most block in Figure 2.

Description of Core Transportation System Modeling Processes

To quantify the potential demand function of the SATS, we employ a traditional multistep modeling process to study travel behaviors. The multistep modeling process includes:

- Trip generation,
- Trip distribution,
- Mode choice, and
- Trip assignment.

The core processes and their array interdependencies are shown schematically in Figure 5. In the trip generation model, trips are produced from an origin (O_i) and attracted to a destination in each county (D_j). Using O_i, D_j, and an observed trip table, a gravity model is calibrated and applied to generate a trip interchange table (T_{ij}). Combined with a suitable mode choice model, the trip table is further divided into several trip tables by each mode (T_{ijm}). A brief description of each process is presented in the following paragraphs.

Definition of Scenario

Any transportation study starts with the definition of the scenario to be studied (see Block 2 in Figure 2). The study of intercity travel usually requires the consideration of large areas around the region of interest, to appropriately capture realistic trips where modal competition exists. Given the performance of current and projected technology business jets, high-performance turboprops and advanced technology single-engine and multiengine piston-powered aircraft, the area of interest for this study encompasses the complete continental United States. This area includes 3,091 counties used as trip generators and attractors, 3,181 public airports with hard runways with runway length greater than 3,000 ft that serve as potential focal points of future SATS and GA activity. The size of the region of

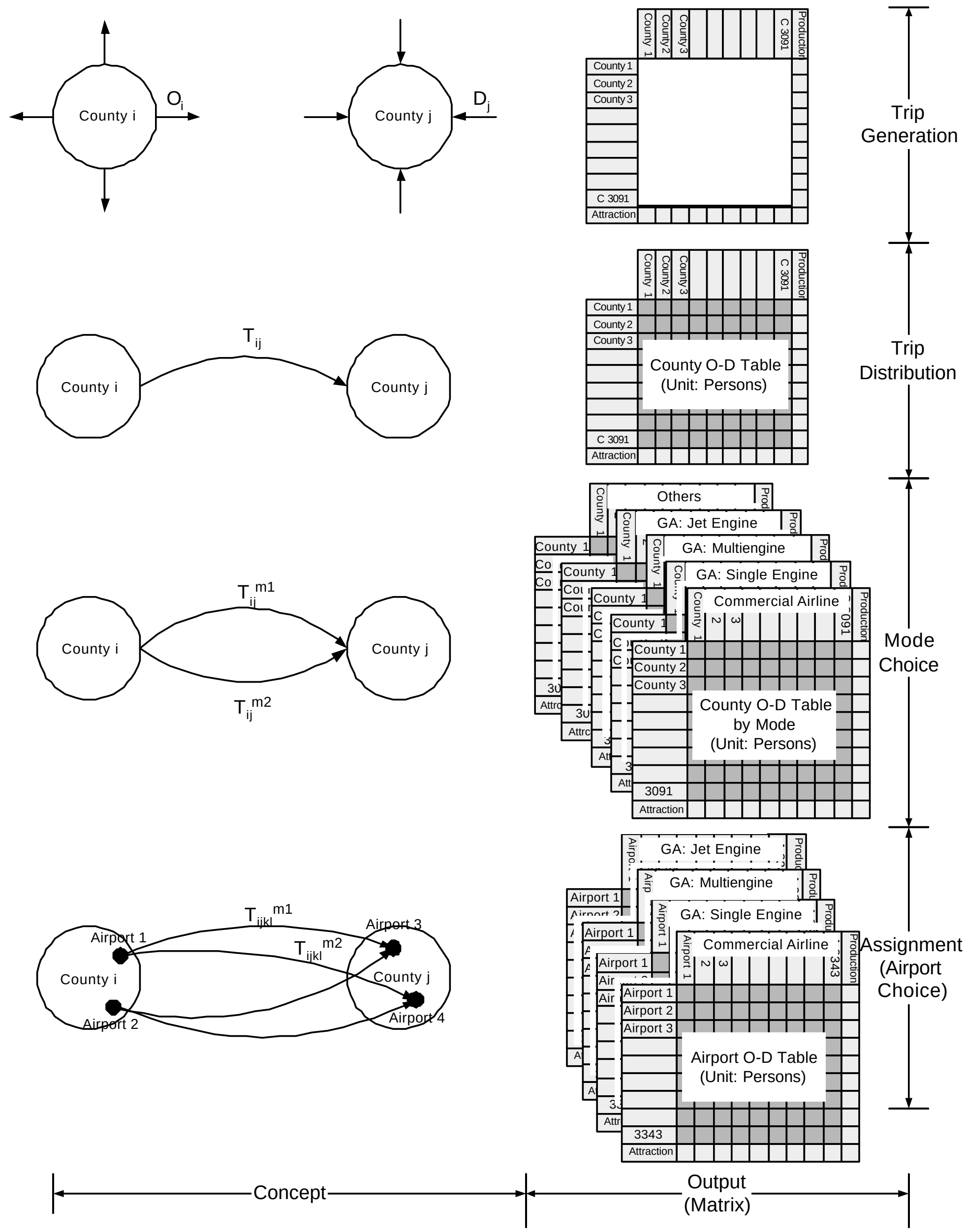


FIGURE 5 Core multistep intercity transportation analysis process.

study is also selected in the context of the average intercity trip distances observed from actual surveys. According to the 1995 American Travel Survey (ATS) (*5*), the average intercity business trip distance was 448 statute mi. Nonbusiness trips average 361 statute mi. The proposed range of SATS light jet aircraft could span up to 1,700 nautical mi, easily encompassing these intercity distances, and making transcontinental trips possible with one stop.

The smallest unit considered in this analysis is the county. Counties range in size from a few to several hundred square miles, and their socioeconomic properties are well documented in the literature (*6, 7*). Socioeconomic characteristics inside each county are modeled using trip-rate tables that vary with income and education levels (Trani et al., *SATS Transportation Transportation System Baseline Assessment Study*, Virginia SATS Alliance Report, Sept. 2002). In this way, the analysis can approximate travel behaviors specific to each county based on specific socioeconomic characteristics of the county. This approach achieves a balance between computational efficiency (so that not every person is modeled individually) and adequate traveler stratification of behaviors within a county.

Trip Demand Analysis

In the study of the SATS as a feasible transportation system, it is imperative to demonstrate that a demand function exists to support the system. Without a careful demand estimation for SATS services, it will be impossible to estimate the cost–benefits of the system and the influence that the four technical capabilities have in the life cycle of the program. In fact, it can be argued that identifying the demand function for the SATS is the first necessary step to demonstrate the practicality of the overall concept. The ultimate goal of trip demand analysis in the proposed methodology is to estimate how many flights, by aircraft type, including SATS flights, will operate from thousands of public airports into the NAS at specific times of the day today and into the future. The resulting trip demand will eventually be used to measure broader impacts of SATS on society. Some examples of impacts are

- Airspace conflicts that drive the provision of air traffic control resources,
- Airport delays,
- Noise levels around airports,
- Air pollution, and
- Regional and national economic benefits.

In other words, all the secondary effects resulting from the deployment of the SATS are intrinsically tied to SATS traffic demand.

A trip-generation model has been developed as part of the process and calibrated using observations taken during the base year (i.e., 2000 in our analysis) by means of a variety of trip surveys (the ATS and Bureau of Census data). The ATS is a large database containing more than 540,000 person-trips in the United States. We employed a cross-classification model for the trip production analysis and a regression model to execute the trip attraction analysis (Trani et al., 2002). Figure 6 shows schematically the steps involved in the trip demand analysis process. The same figure illustrates that the output of this procedure is an O-D matrix with two vectors: one for productions (i.e., trips produced at a county *i*) and one for attractions (trips attracted to county *j*).

Trip Distribution Analysis

The purpose of this step is to derive a realistic O-D matrix to predict travel patterns between centers of transportation activity—counties, in our case (refer to Block 5 in Figure 2). Trip distribution analysis is performed using a doubly constrained gravity model. This process results in a large trip interchange matrix showing the number of trips between O-D counties (see Figure 5). The gravity model uses two calibration factors to model a travel impedance function and a county specific adjustment factor. The model employs calibration coefficients for both business and nonbusiness trips at the state level (Trani et al., 2002). The calibration of the impedance factors in the gravity model is executed at the state level using observed trips from the ATS (*5*).

Mode Choice Analysis

The mode choice model predicts the percentage of person-trips selecting each mode of transportation while traveling between two zones in the region of interest. The GA mode competes with automobile, commercial airline, bus, train, and so forth. Figure 5 illustrates that in the mode choice model, the trip interchange matrix obtained in the trip distribution step is decomposed into a number of trip interchange matrices consistent with the number of modes studied. In our analysis, five O-D matrices were produced, representing the following:

1. Ground modes (called “others”),
2. GA single-engine aircraft,
3. GA multiengine,
4. GA jet, and
5. Commercial aircraft (CA).

Note that the output matrices of the mode choice step shown in Figure 5 are defined at the county level.

The current state of the integrated SATS model uses diversion curves derived from ATS data. A sample diversion curve extracted from ATS data is shown in Figure 7. However, the modal split process to execute this step in future years, from a simulation standpoint, requires a model that explicitly quantifies attributes related to the trip maker and to the various modes of transportation available to complete a trip. The use of a nested multinomial logit model or the use of fuzzy set theory is being explored to expand the capabilities of the analysis. The mode choice modeling techniques adopted in the future will incorporate SATS cost economics derived from a separate aircraft cost model.

Trip Assignment

Trip assignment places the O-D flows for each mode on specific routes of travel through the air transportation network. In this step, the airport–airspace network interactions are studied to assess the impact of SATS operations in the NAS. In this step, the goal is to convert an airport-to-airport person trip O-D table by aircraft type to an airport-to-airport aircraft O-D table using average occupancy rates. Figure 5 illustrates the trip assignment process, which includes a pseudogravity model to estimate the most likely airports used in every trip. This pseudogravity model uses attractiveness factors such as airport activity (i.e., number of based aircraft) and access distance from county centroids to an airport as explanatory variables to assign flight operations to each one of the 3,346 airports modeled.

Air Transportation Network Analysis

This step measures the LOS of the air transportation network in which the SATS and other air transportation vehicles operate. Transportation measures of effectiveness (MOEs), such as travel time, intermodal connection efficiency, delays, aircraft safety, and energy use provide a way to measure the potential impact of the SATS program. These MOEs are necessary because the LOS offered in any transportation network affects the demand function of the system in the future. That is, people adjust their travel behavior to improve the efficiency of travel as much as possible.

Figure 8 illustrates graphically how the network system analysis step relies on several airspace and traffic flow models. Specifically, trips are converted into flights and injected into the NAS according to some concept of operation (CONOPS). A suitable aircraft performance model is used to generate SATS trips using realistic aircraft performance parameters. NAS sector and FAA Special Use Airspace databases are used in coordination with the planned CONOPS to produce credible four-dimensional trajectories of SATS, GA, and CA flights. Hourly demand factors derived from current GA and CA operations are used to derive SATS flights with time tags. These fully prescribed space-time flights are then modeled in two fast-time simulation models: microscopic, such as the Total Airspace and Airport Model (TAAM) or the FAA airfield and airspace simulation model

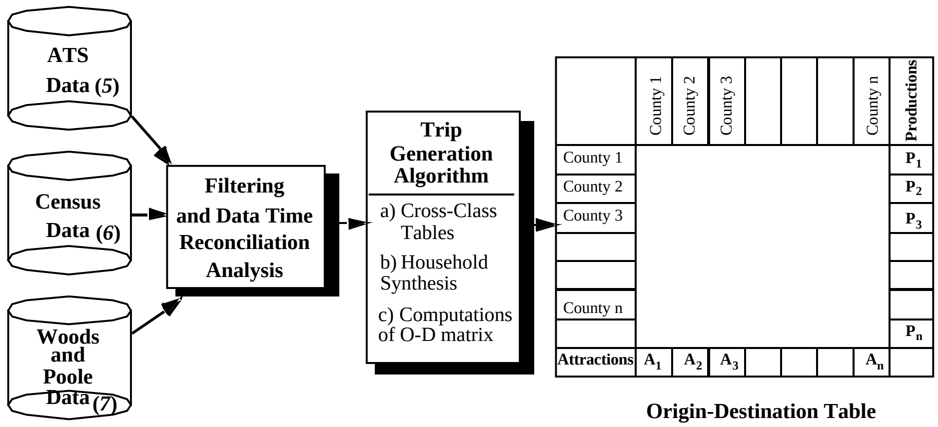


FIGURE 6 The intercity trip demand generation analysis process.

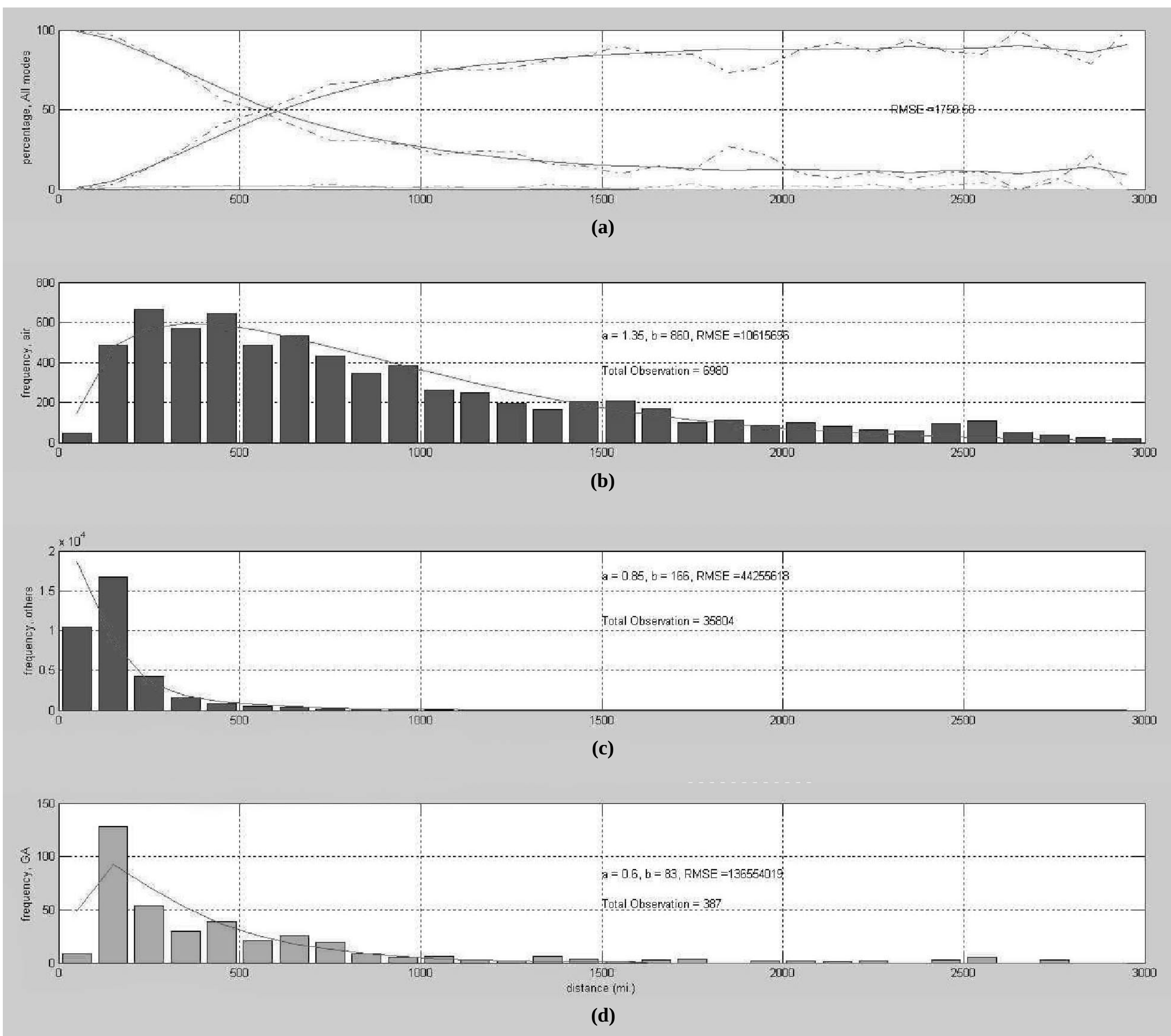


FIGURE 7 Diversion curve and curve fitting using Weibull Function (business trips and income Group 2) for (*a*) percentage of all modes, (*b*) frequency of air travel, (*c*) frequency of other modes, and (*d*) frequency of GA.

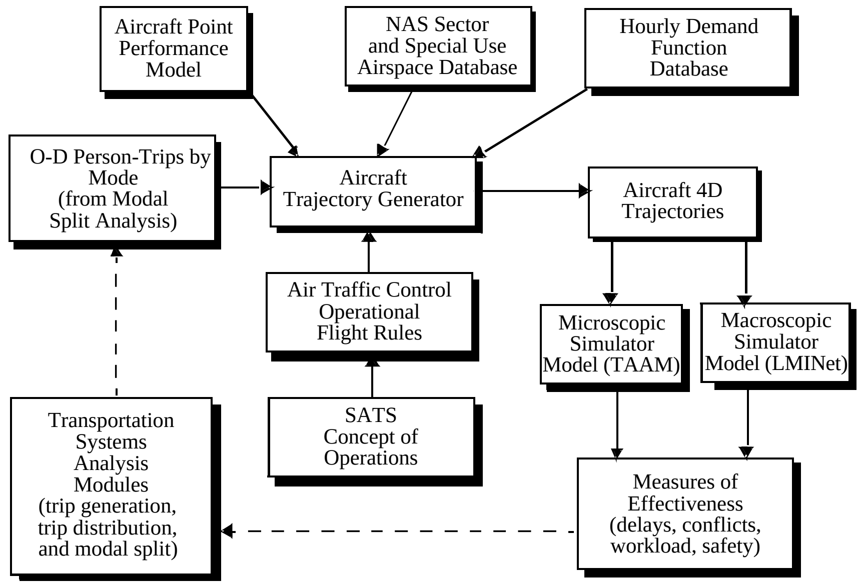


FIGURE 8 Interactions between transportation network analysis and other core transportation systems analysis modules.

(SIMMOD); and macroscopic models, such as the Logistics Management Institute (LMI) SATS network model to study the network effects of SATS impacts. Initially, the same modeling framework has been used to derive a credible baseline scenario (i.e., one without SATS) including performance metrics such as delays, conflicts in sectors, delays at airports, capacity constraints, and so forth.

These baseline results are necessary to understand the changes to the system once the SATS is introduced into the NAS. Figure 9 shows output of the integrated air transportation model for 2000 (the base year of the analysis). The figure contains a distribution of the number of aircraft (for three groups of GA aircraft modeled) as a function of one-way travel distance. The same figure also contains a table summary of the number of GA operations in the base year of the analysis. Note that in the year 2000 no SATS vehicles are predicted by the model. However, the numbers of GA operations are reported in a summary table shown in Figure 9.

The flight demand function derived from the baseline model split analysis provides flight plans, including detailed information on each flight such as O-D airports, waypoints, altitudes, and flight times. When there are flight plans in hand, potential airspace conflicts can be derived using airspace modeling and simulation tools such as TAAM, Virginia Tech's Airspace Occupancy Model (AOM), and the Airspace Encounter Model (AEM) (Trani et al., 2002).

Implementation and Preliminary Computational Experience

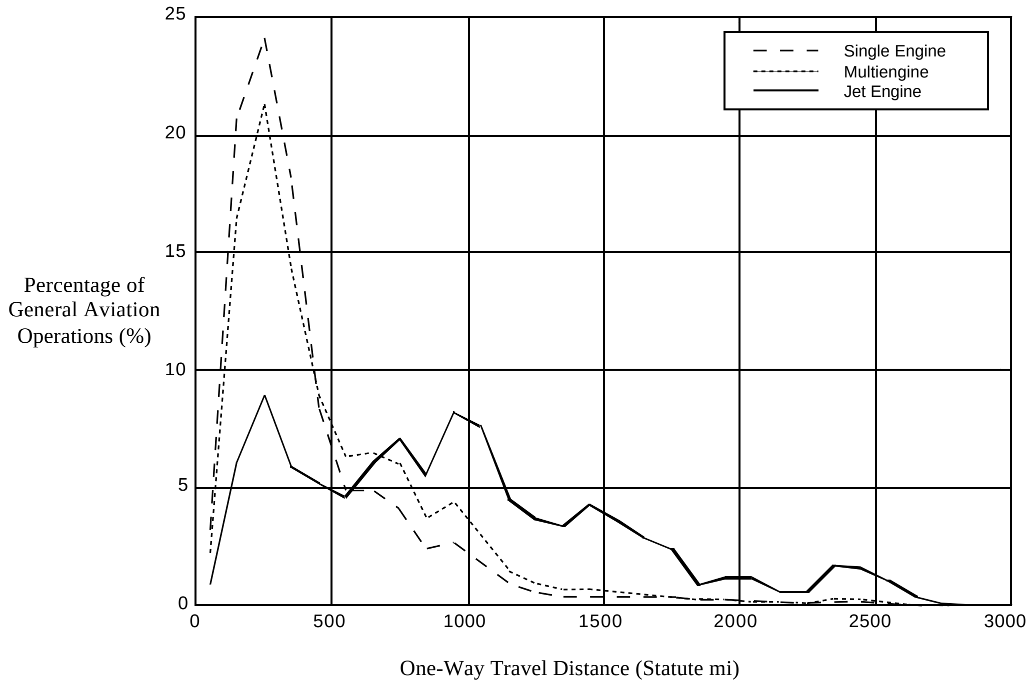
The process described so far encompasses the basic steps used in transportation modeling without apparent feedback (see Figure 2). The algorithms necessary to drive the dynamic behavior of the model are being implemented. This process, illustrated in Figure 2, relies on exogenous predictions of socioeconomic factors into the future and the knowledge of the SATS program policies as the simulation moves forward in time. Preliminary studies related to the four operational capabilities of the concept are being conducted to quantify the degree to which the SATS may provide benefits that can affect public acceptance, that is, whether the SATS can be affordable and yet offer a safe travel mode alternative. Other valid policies that could be tested with the model are the various levels of investment at airports needed to help support the program, necessary adjustments to air traffic control resources to facilitate a SATS operational concept, and many others.

In this study, off-the-shelf software was used to expedite the numerical computations depicted schematically in Figure 2. MATLAB, a software developed by MathWorks Inc. (*8*), is used as a computational engine in the implementation of the multistep planning process. Using built-in MATLAB data structures permits the execution of the procedures in the four core transportation planning submodels in less than 40 min of CPU time with the use of a standard Pentium 4 PC running at 1.7 Ghz. To do the statistical analysis required in the model, the SAS software package was employed (*9*). TAAM (*10*), AEM, and AOM (*11*) have been used as airspace simulation and analysis models to measure the impacts of the SATS in a complex air transportation network.

CONCLUSIONS

Systems engineering analyses, like any airport master plan, are living and evolving works. This paper offers an integrated and comprehensive systems engineering analysis framework to study the SATS as a feasible transportation system. The goal of this project is to integrate acceptable methods to study the effect of SATS operation in the NAS and ultimately quantify whether or not the SATS has merit as a mode of transportation. The ultimate goal of the method proposed here is the development of an integrated decision-making tool that could be used to study the implementation of SATS technology at the regional and national levels.

Skeptics and supporters alike of the SATS concept view the analytical tools as a necessary step to prove under what circumstances the SATS could be a viable mode of transportation. These circumstances include a clear understanding of the levels of safety, affordability of



(a)

Aircraft Type	Average Stage Length (mi)	Total Hours Flown Annually	Total Trip Distance (mi)	Total Number of Operations
Single Engine	292	23,238,000	3,427,000,000	11,742,906
Multiengine	456	11,402,000	3,136,000,000	6,877,066
Jet Engine	791	6,515,000	3,498,000,000	4,418,864
		41,155,000	**10,061,000,000**	**23,038,836**

(b)

FIGURE 9 Initial NAS system conditions estimated by the model (numbers apply to GA aircraft in 2000).

the mode, and assessment of negative impacts such as noise and emissions pollution. After all, the vision of the SATS program is quite appealing. Yet it poses interesting transportation modeling challenges.

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