

# Modeling Research Under NASA/AATT

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FINAL REPORT

## Existing and Required Modeling Capabilities for Evaluating ATM Systems and Concepts

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# 1.0 INTRODUCTION

## 1.1 Background

ATM systems throughout the world are entering a period of major transition and change. The combination of important technological developments and of the globalization of the air transportation industry has necessitated a re-examination of some of the fundamental premises of existing ATM concepts. New ATM concepts have to be examined, concepts that may place more emphasis on: strategic traffic management; planning and control; partial decentralization of decision-making; and added reliance on the aircraft to carry out strategic ATM plans, with ground controllers confined primarily to a monitoring and supervisory role. 'Free Flight' is a case in point.

In order to study, evaluate and validate such new concepts, the ATM community will have to rely heavily on models and computer-based tools/utilities, covering a wide range of issues and metrics related to safety, capacity and efficiency. The state of the art in such modeling support is adequate in some respects, but clearly deficient in others. It is the objective of this study to assist in: (i) assessing the strengths and weaknesses of existing fast-time models and tools for the study of ATM systems and concepts and (ii) identifying and prioritizing the requirements for the development of additional modeling capabilities in the near future.

A three-stage process has been followed to this purpose:

1. Through the analysis of two case studies involving future ATM system scenarios, as well as through expert assessment, modeling capabilities and supporting tools needed for testing and validating future ATM systems and concepts were identified and described.
2. Existing fast-time ATM models and support tools were reviewed and assessed with regard to the degree to which they offer the capabilities identified under Step 1.
3. The findings of 1 and 2 were combined to draw conclusions about (i) the best capabilities currently existing, (ii) the types of concept testing and validation that can be carried out reliably with such existing capabilities and (iii) the currently unavailable modeling capabilities that should receive high priority for near-term research and development.

It should be emphasized that the study is concerned only with the class of "fast time" analytical and simulation models. "Real time" models, that typically involve humans-in-the-loop, comprise another extensive class which is not addressed in this report. However, the relationship between some of the fast-time models reviewed and a few well-known real-time models is identified in several parts of this report and the potential benefits from the combined use of these two classes of models --a very important subject-- are discussed in Chapters 4 and 7.

## 1.2 Outline of the Study and Contents of the Report

This section provides an outline of the contents of the study and of the structure of this report. To perform the three-stage process identified in Section 1.1, the project was subdivided into three tasks. Task 1, on the identification of future modeling requirements, examined two case studies involving future concepts, one a concept for the entire ATM system and the other for an ATM subsystem. These two case studies were specified in consultation with NASA.

The first case study concerns requirements for modeling the Free Flight concept. An initial review of such requirements was carried out during the early stages of the study and its findings are presented in Appendix A. This initial review indicated that there are major aspects of Free Flight which cannot be addressed adequately by existing models and that extensive additional model development would be needed to correct this problem. For this reason, the Free Flight case study was re-examined later in the project to develop more specific recommendations about corrective measures. These recommendations are summarized in Chapter 7 along with the other findings of the study.

The second case study examines modeling requirements for Airport Surface Traffic Management (ASTM) Automation, a concept for improving the safety and efficiency of airport surface operations currently under intensive investigation in both the United States and Western Europe. The findings of this second case study, which also identified several important challenges and gaps with respect to modeling ASTM Automation, are presented in Appendix B.

Task 2 ("identification and review of existing models and tools/utilities") consisted of three parts. Part 1 identified the most important existing models of ATM and airport operations. To this effect, an extensive literature review was carried out using several bibliographic sources and yielding several hundred references corresponding to such keywords as "ATC models", "airport capacity", "trajectory optimization", etc.

A set of formal and informal criteria were then used to select, from this long list, a subset of models that deserved a detailed review. The formal criteria required the models to be: (i) "fast time"; (ii) already implemented through a computer program; (iii) utilized, currently or in the past, in a study or studies of some aspect of ATM and/or airport operations; and (iv) available in the public domain, be that at no --or nominal-- cost or through a vendor. At a more informal level, peer recommendations played an important role in selecting a preliminary list of models as candidates for detailed review. For this purpose, members of the study team visited some of the principal agencies or organizations engaged in ATM and airport modeling in the United States (FAA, MITRE CAASD, CSSI and LMI) and in Europe (Eurocontrol, DLR, NLR, CENA and CAA/NATS). During these meetings models available or being utilized at these organizations were identified and a number of specific models were discussed in detail with competent staff members. In addition, numerous contacts were made by telephone or in person with individuals in other organizations, aimed at identifying important existing models. The list of models compiled through this

process was finally reduced further by eliminating any models which, in the opinion of the study team, were clearly superseded by others. For example, ADSIM and RDSIM, two models that have been used extensively by the Federal Aviation Administration (FAA) to carry out studies of capacity and delay at many of the busiest airports in the United States, were not reviewed in detail because they were deemed to have been superseded by such models as SIMMOD, TAAM and the Airport Machine. Similarly, such well-known analytical models as Blumstein's runway capacity model, were not reviewed since their best features were found to have been incorporated into other, more recent models.

This selection procedure eventually yielded a total of 27 models, identified in Table 1.1, which were studied in detail during Part 2 of Task 2. The summary reviews of these models appear in this report. Table 1.1 also allocates the 27 models into nine groups, according to the primary outputs of the models, the methodology used (analytical or simulation --see also Chapter 2) and their level of detail.

It is almost certain that some models, which are important in the view of some or many in the ATM community, are not among the ones listed in Table 1.1. Such omissions are practically unavoidable in a field in which there is much ongoing activity and research and where some models are developed primarily for internal use, but are then considered by their developers as "available for use by others". Any glaring gaps can, however, be filled up in the future. The intent of this report is that it serve as a "living document" whose contents and conclusions can be updated periodically. The latest version of the report will be maintained in the address

<http://web.mit.edu/aeroastro/www/labs/AATT/aatt.html>

on the Worldwide Web. Readers who wish to suggest changes or additions to the report are encouraged to contact Professor Amedeo R. Odoni at +1-617-253-7439 or at [odoni@mit.edu](mailto:odoni@mit.edu). We also note that many other Web sites exist with current information about models of ATM and airport operations. The principal ones identified by this study are listed in Appendix C at the end of this report.

The reviews of the individual models constituted the most time-consuming part of the study. A summary of the findings of each review, ranging in length from two to seven pages, was prepared. Each summary consists of 13 sections (see Section 1.3 below for full details) addressing various model characteristics, such as principal inputs, principal outputs, main assumptions, computational characteristics, model availability, etc. Each review ends with a summary evaluation that offers an overall appraisal of the usefulness of the model and identifies specific strong and weak features.

The model reviews were carried out by using a combination of approaches. In all cases, available documentation was studied and at least one interview was conducted with either a developer of the model or an experienced user. Hands-on experience was also obtained (directly or indirectly) whenever possible, specifically with the following twelve models: LMI Runway Capacity Model, FAA Aifield Capacity Model, DELAYS, AND, SIMMOD, TAAM, ASCENT, RATSG, MIDAS, ACIM, INM and NOISIM. For the

### Table 1.1: Models Reviewed

1. Quasi-Analytical Models of Airport Capacity and Delay (FAA Airfield Capacity Model, LMI Runway Capacity Model, DELAYS, AND)
2. High - Level - of - Detail Simulations of Airport Operations (HERMES, The Airport Machine)
3. High - Level - of - Detail Simulations of Airport and Airspace Operations (TAAM, SIMMOD)
4. Intermediate - Level - of - Detail Simulations of Airport and/or Airspace Operations (NASPAC and spin-offs, TMAC, FLOWSIM, ASCENT)
5. Safety Models (TOPAZ)
6. Conflict Resolution, Workload Measurement and Airspace Management (RAMS, Arc 2000 [+HIPS], BDT, NARSIM, ASIM, SDAT, RATSG)
7. Human Factors; Man/Machine Integr'n (MIDAS, PUMA, DORATASK)
8. Cost-Benefit and Investment Models (NARIM, ACIM)
9. Noise Models (INM, NOISIM)

other fifteen models listed in Table 1.1, it was not feasible to obtain such experience, either because the models were not transportable or because obtaining access to them was beyond the project's resources. However, in all but six cases (HERMES, FLOWSIM, TOPAZ, SDAT, DORATASK and NARIM) it was possible to arrange for demonstrations of the models to one or more members of the project team.

The third part of Task 2 was concerned with identifying and reviewing some generic utilities and tools that are often important in modeling airport and ATM operations. Examples include: demand generators, i.e., programs that generate demand schedules having certain user specified characteristics such as a given distribution of demand by time of day; aircraft itinerary generators which create itineraries of aircraft during the course of a day that resemble the itineraries typically flown by airline fleets; and weather generators which provide weather inputs on a local (e.g., an individual airport) or regional basis (e.g., a moving weather front). The common characteristic of these "generic utilities and tools" is that they are useful in numerous contexts and, if available, would be highly applicable with many of the models listed in Table 1.1.

Finally, Task 3 combined the findings of Tasks 1 and 2 to draw conclusions about the best capabilities currently available, as well as to prepare a set of recommendations for future research and development efforts on ATM modeling. These conclusions are presented in five parts of this report: the introductory sections of Chapters 2, 3, 4 and 5 dealing respectively with

models concerned with (a) capacity and delays, (b) conflict generation, detection and resolution, (c) human factors and automation and (d) cost/benefit assessment; and Chapter 7 which summarizes these findings in more general terms.

### 1.3 Format of Model Reviews

As noted above each detailed model review in this report consists of 13 sections. The contents of each section are explained below.

**Item 1: Primary Model Category:** This is a brief descriptor of the principal issue emphasized by the model (e.g., “capacity of the runway system” or “conflict detection and resolution”). Appropriate modifiers can be provided if the model spans more than one subject areas.

**Item 2: Summary:** A brief description of the model (one to three paragraphs). This can consist of the “abstract” provided in the model developer’s documentation, if adequate, or a summary prepared by the evaluators. This section may include an identification of some of the fundamental features of the model, specifically: (i) primary methodology (e.g., analytical model, fast-time simulation, real-time simulation, AI/knowledge-based model, etc.); (ii) level of detail (microscopic vs. macroscopic approach); (iii) principal “competing” models (identifies other models in the same area).

**Item 3: Input Requirements:** Identifies the most important inputs necessary to run/use the model. Also identifies, when applicable, databases accompanying the model, availability of default inputs, etc.

**Item 4: Outputs:** Identifies the major outputs obtainable from the model.

**Item 5: Major Assumptions:** Lists the major assumptions of the model with remarks, when appropriate, on their reasonableness. Also notes aspects of real-world operations which may be omitted by the model.

**Item 6: Computational Characteristics:** Indicates whether a computer program has been written to implement the model in question. If a computer program does exist, the items covered (whenever such information is available) include: computer language used; hardware and software requirements; typical running times for the model; graphics or other interfaces; quality of model documentation; model support by sponsoring organization; amount of effort needed to learn how to use the model and to set up inputs for computer runs. To assist in compiling this information a brief questionnaire was prepared to be completed by the developer of the model or someone very familiar with it. The questionnaire can be found in Table 1.2 at the end of this section.

**Item 7: Modularity and Flexibility:** An indication as to how easily the model can be extended to include additional considerations and extensions. Comments may also be made on the possibility of combining the model with others to provide a tool of expanded scope.

**Item 8: Status of Model:** Indicates, whenever this information is available, whether the model in question is being actively used at this time, whether further model development is in progress, etc.

**Item 9: Extent of Model Validation:** Information on whether or not the model has been validated, and if yes, in what way.

**Item 10: Principal applications:** Identifies the types of issues that the model is best suited to address. Also provides examples, if any, of projects in which the model has been used in the past.

**Item 11: Model Availability:** Identifies the model's supplier or vendor, if applicable, or model's sponsoring organization. Costs are given, if appropriate. Contact person(s) are identified if possible.

**Item 12: Information Base for Model Evaluation:** Identifies the means employed to prepare the evaluation of the model (interview(s), papers reviewed, other documentation reviewed, hands-on experience, etc.). Documents describing the model should be identified in detail (title; author(s); organization generating the report; report number; date; other identification information --such as NTIS number or sponsoring government agency, if any).

**Item 13: Summary Evaluation:** Offers the evaluator's appraisal of the value and usefulness of the model on an absolute basis and, if possible, by comparing it to other models in the same area. Specific strong and weak features of the model should be listed to provide guidance and assistance to potential users of the models or to future researchers in this area.

**Table 1.2: Computational requirements questionnaire**

1. Does code exist? ( Y / N )	
2. Required operating system(s)	
3. Hardware requirements	1. Platform(s): 2. Memory (RAM and hard drive) 3. Other (tape drive, input devices, monitors)
4. Software / compiler requirements:	
5. Contact / availability of support:	
6. Evaluations (list major deficiencies / strengths):	1. Documentation ( Poor / Adequate / Good ) 2. Startup effort / default inputs ( Low / Moderate / High) 3. User interface ( Poor / Adequate / Good ) 4. Typical run time:
Name: _____ Date: _____	

## 1.4 Participants

The following individuals, all associated with the MIT's Department of Aeronautics and Astronautics, comprised the study team:

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## 2. CAPACITY AND DELAY MODELS

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### 2.1 REVIEW OF CAPACITY AND DELAY MODELS

#### 2.1.1 Definition

Capacity and delay are two of the principal measures of performance of air traffic management (ATM) systems. To obtain estimates of these measures, a considerable number of models have been developed over the years. Indeed, this is the oldest area of model development in the ATM field, with the first significant models dating back to the late 1950s. It is also the area where the most advanced modeling capabilities currently exist. There is still, however, much room for improvement, as this section will indicate.

It is useful to classify capacity and delay models according to three aspects: *level of detail*; *methodology*; and *coverage*. With respect to the first, we classify models into *macroscopic*, *mesoscopic* and *microscopic*, corresponding respectively to a low, intermediate and high level of detail. While the boundaries among these three classes are not particularly sharp (e.g., the same model might be characterized as “low-level-of-detail” by some or “intermediate-level” by others) it is nonetheless very useful to classify models along these lines. Macroscopic models omit a great deal of detail, since their objective is to obtain approximate answers with emphasis on assessing the *relative performance* of a wide range of alternatives. For example, air traffic demand may be described in such a model by simply an hourly rate of arrivals at an element (airport, sector, etc.) of the ATM system and a simple probabilistic description of how these arrivals occur over time (e.g., “Poisson arrivals”). These models are used primarily for policy analysis, strategy development and cost-benefit evaluation. Ideally they should be fast, in terms of both input preparation and execution times, so they can be used to explore a large number of “scenarios”.

Mesoscopic models, while more detailed than macroscopic ones, are still rather strategic in nature. For example, a mesoscopic model may be concerned with aggregate flows per unit of time through one or more elements of the ATM system (e.g., for flow management purposes) without being concerned with how these flows are handled, as long as the flows remain below some pre-defined “capacities”.

Finally, microscopic models are designed to deal with more tactical issues. Typically, such models represent aircraft on an individual basis and move them through the ATM elements under study by taking into consideration each aircraft’s performance characteristics. Such detailed features as conflict resolution, airport taxiway and gate selection, pushback maneuvering, etc., are generally included only in microscopic models.

With respect to methodology, we distinguish between *analytical* and *simulation* models. The former are abstract, necessarily simplified mathematical representations of airport and airspace operations. By manipulating these expressions (either in closed form or numerically) analytical models derive estimates of capacity and delays in airspace and/or airports. In contrast, the classical approach of simulation modeling is to

create objects (typically aircraft) which move through the airspace segments and airports of interest. By observing the flows of such objects past specific locations (e.g., the threshold of a runway or an en route waypoint) and the amount of time it takes for aircraft to move between such points, the simulation models compute appropriate measures of capacity and delay. There is a strong correlation in practice between methodology and level of detail: specifically, analytical models tend to be mostly macroscopic in nature, whereas most simulations are mesoscopic or microscopic.

Models (whether analytical or simulations) can be further distinguished in terms of methodology, according to whether or not they are (a) *dynamic* and (b) *stochastic*. Dynamic models will accept input parameters which are time-dependent and will capture the fluctuations over time in the performance metrics of airports and/or airspace traffic. Similarly, stochastic models will accept input parameters which are specified probabilistically (i.e., are random variables) and will capture the impacts of uncertainty on the performance metrics of airport and/or airspace traffic. Stochastic *simulation* models are often referred to as *Monte Carlo* simulations.

Finally, with respect to coverage, we classify capacity and delay models according to whether they encompass operations of the following elements of airports and airspace: (1) aprons and taxiways; (2) runways and final approaches; (3) terminal area airspace; and (4) en route airspace. Combinations of more than one of these components are, of course, possible so that some models may be able to examine an airport in its entirety, or even a national or regional system of airports, terminal areas and en route sectors.

### 2.1.2 Principal Existing Models

Table 2.1 lists the models reviewed in this report, classified according to level of detail and coverage. Models which are analytical are indicated with an asterisk; the remaining models are simulations.

Existing **macroscopic** models concentrate on runway capacities and associated delays or on en route sector operations. General purpose, macroscopic models of taxiway/apron operations and of terminal airspace operations do not exist, because such models need to be location-specific. Of the runway/final approach models listed in Table 2.1, the top two estimate capacity, while DELAYS and AND estimate airport-related delays.

The LMI Runway Capacity Model is still under development and, at this point, covers only single-runway airports in general form. For any given aircraft mix and set of separation requirements, it computes (1) the all-departures capacity of a runway, (2) the all-arrivals capacity, (3) the number of “free” departures that can be performed without reducing the all-arrivals capacity and (4) the capacity of the runway if a departure is always inserted between two arrivals, so that arrivals alternate with departures on the runway. The capacity of the runway for any other mix of arrivals and departures and any other sequencing of arrivals and departures can then be computed approximately by utilizing the four estimates above. (For configurations involving the simultaneous use of more than one runway, the model has to be extended on an *ad hoc* basis for each airport.) The FAA

Airfield Capacity Model computes the capacity of 14 different common runway configurations, ranging from one to four simultaneously active runways. Its logic differs in several significant respects from that of the LMI Model. DELAYS views the runway system of an airport as a queueing system whose "customers" are aircraft demanding to land or take-off and whose capacity is equal to the arrival, departure or total capacity of the runway system, depending, respectively, on whether one is interested in delays to arrivals, to departures or to the "average operation". The model is based on a fast approximation scheme for solving the differential equations that describe a quite general dynamic queueing system. The Approximate Network Delays (AND) model is a complex extension of DELAYS that considers a network of airports, instead of a single airport, and computes how delays in any part of that network would "spread", due to disruption of airline schedules, to the rest of the network. The model's intent is to help evaluate the system-wide implications (on a national or regional scale) of changes in (i) the capacity of one or more airports and/or (ii) the amount or geographical distribution or temporal distribution of airport demand.

**Table 2.1: Classification of Analytical and Fast-Time Simulation Models of Capacity and Delay**

Level of Detail (type of study)	Scope of Model			
	Aprons and taxiways	Runways and final approaches	Terminal area airspace	En route airspace
<b>Macroscopic</b> (Policy analysis, cost-benefit studies)		LMI Runway Capacity Model* FAA Airfield Capacity Model* DELAYS* AND*		ASIM SDAT* DORATASK
<b>Mesoscopic</b> (Traffic flow analysis, cost-benefit analysis)		NASPAC TMAC FLOWSIM ASCENT		
<b>Microscopic</b> (Detailed analysis and preliminary design)	T A A M SIMMOD			
<b>Same</b>	The Airport Machine HERMES		RAMS	

\*indicates an analytical model

Of the en route macroscopic models, ASIM and DORATASK are fast approximate simulations for computing, respectively, the expected number of aircraft conflicts and the expected controller workload, in a single sector or in a set of sectors, that would result from any given pattern of traffic flows along a structured set of airways. SDAT is an analytical model that, for some given pattern of traffic flows, would support the design of en route sectors with the objective of minimizing sector workload resulting from the routine handling of traffic, as well as the resolution of conflicts. Thus, the principal focus of all three of these models is on controller workload and on aircraft conflicts (see also the next Section). They are

related, however, to capacity and delay in the sense that en route sector capacity is largely determined by controller workload, which, in turn, is influenced heavily by the potential number of conflicts that a controller may be called on to resolve.

The four **mesoscopic** models listed in Table 2.1 are all recent (the oldest, NASPAC, was initially developed in 1988). NASPAC was initially designed as a national- or regional-scale, macroscopic simulation whose objective, like that of AND, was to study a network of airports and compute how delays in any part of that network would “spread”. However, many details were subsequently added to NASPAC, so that today it is primarily used to deal with traffic flow management (TFM) issues, rather than predictions of capacity and delay. The focus of the other three models listed, FLOWSIM, TMAC and ASCENT is also on TFM. TMAC, a model under continuing development at MITRE) has also been used recently in connection with the preliminary evaluation of some of the benefits that may be obtained from the Free Flight concept. Of the three models, FLOWSIM is the most mature, while new capabilities are currently being added to the other two, especially the ASCENT model of the C.S. Draper Laboratory, which is being expanded to cover both strategic and tactical aspects of TFM.

An important distinction in the case of **microscopic** models is between *node-link* and *3-dimensional (3D)* models. Node-link models discretize airports and airspace into a number of nodes and links. Aircraft move from node to node along the links and conflicts occur when more than one aircraft try to move to a single node. These conflicts are resolved by delaying one or more of the aircraft at a node. By recording the amount of delay incurred at each node by each aircraft, the model compiles the requisite aggregate and distributive delay statistics. SIMMOD and The Airport Machine are node-link microscopic models, as are ASIM and FLOWSIM among the macroscopic and mesoscopic models, respectively.

3D models allow aircraft to fly arbitrary three-dimensional routes. (When simulating airport surface traffic operations, these are, of course reduced to 2D models.) In some 3D models, aircraft follow specified flight plans exactly; in others, aircraft dynamics equations are used to simulate aircraft performance. Flight paths may thus deviate from planned flight plans. RAMS, TAAM and HERMES are microscopic 3D models —and so are TMAC and ASCENT among mesoscopic models.

Most of the models in the microscopic category are well-known. SIMMOD, TAAM and The Airport Machine have been used in numerous airspace and/or airport studies in many parts of the world. The former is a model developed with support from the FAA and is available at little direct cost, while the latter two are proprietary and carry significant license fees. SIMMOD and TAAM cover both airspace and airport operations, while The Airport Machine is limited to airport operations only. RAMS is an airspace operations modeler, developed recently by Eurocontrol, which also controls its availability. The least-known model, HERMES, has been developed by CAA/NATS in the UK and its use is currently limited to simulating in detail operations at London’s Heathrow and Gatwick Airports.

### 2.1.3 Individual model assessment and model comparisons

We now identify briefly some strengths and weaknesses of the models in Table 2.1 and summarize some comparisons among models with overlapping scope.

Beginning with **macroscopic** models, we observe that their potential has not yet been fully attained —nor is it adequately appreciated by the user community. In the area of airport capacity estimation, for example, a fully general, macroscopic model would be extremely valuable and is within easy technical reach. The LMI Runway Capacity Model includes some outstanding features (robust probabilistic approach, adoption of an air traffic controller's viewpoint) but is currently limited to a single runway and has certain gaps in its logic. The FAA Airfield Capacity Model, by comparison, covers many important multi-runway configurations, but its fundamental building block (i.e., the underlying single-runway capacity model) has some fundamental weaknesses. An excellent opportunity exists to combine the best features of the two models to arrive at a robust, fast and quite accurate analytical model to compute the capacities of all but the most complex runway systems. Similarly, DELAYS can provide very adequate support for most policy-oriented studies, typically concerned with approximate estimates of delay costs and relative performance of a set of alternatives for expanding an airport or managing demand there. The principal deficiency of DELAYS is its aggregate nature: it does not distinguish among individual aircraft or types of operations, when these aircraft or operations share the same runway. For example, when a runway is being used for a mix of arrivals and departures, DELAYS will compute an average delay for all operations, without considering the fact that arrivals often receive priority over departures. This priority assignment means that in practice arrivals may incur less delay and departures more than the average value computed by DELAYS.

AND also represents a potentially important technical development in its ability to approximately model analytically an entire system of airports and the associated delays. As such, it could emerge in the future as a superior alternative to NASPAC and other system-wide simulation models, because of its speed, simplicity and statistical robustness. However, the model is not yet portable (it is available only at MIT and at MITRE) and its user interface is still quite primitive. A more fundamental weakness is that AND is exclusively concerned with airport-related delays. Thus, it is more applicable to an environment, such as that of the United States, where most delays are indeed airport-related, than to one where en route sectors are also heavily congested, as is the case today in much of Europe.

As we noted above, the en route macroscopic models, ASIM, SDAT and DORATASK are only indirectly concerned with capacity and delay, since their focus is on workload measurement and estimation of the expected number of conflicts in en route airspace. A common characteristic of these models is that they are new and experience with them is, as yet, insufficient to make any definitive judgment on their usefulness. All three are discussed in somewhat more detail in Section 3.

**Mesoscopic** models, as mentioned earlier, are also relatively new and can be said to be currently in a state of transition from “first” to “second”

generation. The only one among these models with which extensive experience already exists is NASPAC. This experience has been mixed, with long turnaround times, high cost and results of occasionally questionable validity. Recent enhancements to the model carried out in France, at MITRE and by the FAA may have overcome some of these problems. FLOWSIM may emerge as a viable and much faster alternative to NASPAC for studies of flow management strategies, as it utilizes advanced software technology. However, FLOWSIM does not model en route airspace and thus, like AND, is more applicable to the United States ATM environment than that of Europe. Experience with FLOWSIM to date has been limited. TMAC and ASCENT are far more complex mesoscopic simulation environments than NASPAC and FLOWSIM and incorporate now (and especially in their future plans) many additional capabilities, including some tactical aspects of TFM. However, both models are still in (quite advanced) developmental stages and are not portable at this time.

In the area of detailed (**microscopic**) simulation models, there are some interesting comparisons to be made among the three dominant airport simulation models. SIMMOD can be acquired at very low cost (\$250 for the PC version, \$3,900 for the workstation version) and provides a lot of options and flexibility and adequate stochastic features. On the negative side, SIMMOD is very labor intensive, requires a truly expert user, has a poor user interface, provides few diagnostics and “crashes” easily, especially the PC version. The Airport Machine, which costs about \$20,000 for a site license, offers less flexibility and options than SIMMOD and is a largely deterministic model. But it is less labor-intensive than SIMMOD (still, however, requiring considerable resources and training), provides for interactive use and offers good graphics capabilities. Finally, TAAM is expensive (\$350,000 for a site license, \$14,000 per month for rental) and has few stochastic features. It offers, however, advanced software engineering features, excellent graphics, an outstanding user interface and a rule-based logic that gives the user many options and flexibility. TAAM, like SIMMOD, is still labor-intensive and requires a considerable amount of user training.

In conclusion, the prospective user of any one of these three detailed airport simulations is faced with several difficult trade-offs (e.g., cost vs. quality of user interfaces vs. model features and flexibility). None can be said to “dominate” the other two. Prospective users should, in any event, be aware that all three models require significant resources and time. As for HERMES, CAA/NATS has reported that its performance at Heathrow and Gatwick has been very satisfactory. It is not clear, however, how generalizable to other airports HERMES is and what will be its future availability, if any, to users other than CAA/NATS.

With respect to detailed **airspace** simulations, 3D models hold an inherent advantage over node-link models, with respect to flexibility. This is especially true when it comes to evaluating concepts, such as Free Flight, which give airspace users the freedom to select their own optimized flight paths. Node-link models are almost completely unadaptable to such an environment. This means that TAAM and RAMS are the two models of choice in this area. RAMS provides more features and flexibility than TAAM, but the latter seems to be better suited to the simulation of large regions of airspace, with multiple sectors, airports, etc. Cost (in the case of

TAAM) and availability (in the case of RAMS which can be accessed only by arrangement with Eurocontrol) are additional considerations. RAMS, in addition, requires a very specific type of platform (HP9000 series 700 workstations).

#### 2.1.4 Collective Model Assessment

Capacity and delay models, as a group, represent the most advanced area of airport and airspace operations modeling. Many of the models in Table 2.1 are “second generation” ones, i.e., have been preceded by other similar models and have benefited from the experience gained from these earlier predecessors. The growing level of model specialization (e.g., the fact that models of the same entities, such as of runway systems, exist at several different levels of detail) is additional evidence of the relatively advanced state of maturity in this area.

Extensive practical experience also exists with many of the models in Table 2.1. There is, therefore, considerable confidence in the ability of capacity and delay models to generate quite realistic results. This is especially true, when these models are used, as they often are, to rank competing alternatives, i.e., to assess the performance of concepts or proposals in relative, not absolute, terms. Even in absolute terms, however, the accuracy of these models has improved considerably for certain types of metrics over the years. For example, runway system capacity can usually be estimated with an accuracy of  $\pm 5\%$  with some of the existing models.

Despite these positive developments, a number of important problems remain in this area. One is the problem of model misapplication: the user community is not sufficiently familiar with the range of models available and often uses the wrong model to address problems at hand. The most typical example is the use of a microscopic model (e.g., SIMMOD or TAAM or The Airport Machine) to address questions that can be answered much more quickly and at much lesser cost by a macroscopic or mesoscopic model.

A more fundamental problem is the large amount of resources (model acquisition costs, training, data collection and, especially, input/scenario preparation) typically required for applications of microscopic and mesoscopic models. This is especially true of studies involving regional systems of airports and associated airspace. Reducing the level of effort and resources associated with the use of capacity and delay models should be an area of emphasis in future work.

A third problem is the adaptability of existing models to new ATM concepts. Recent attempts to evaluate the benefits and costs associated with the concept of Free Flight have brought this problem to the fore vividly. Some models (e.g., the airspace part of SIMMOD) are almost completely unadaptable to a concept that allows each aircraft to select its own optimized flight path in 3D space due to their node-link structure. But even 3D models, such as TAAM, currently lack critical features (e.g., sufficient stochastic options, detailed representation of weather and winds) needed to evaluate essential aspects of the concept. One way to overcome such problems in the future is for the user community to prepare a detailed set of specifications for the features that capacity and delay models should include.

Existing models could then be improved to comply with these specifications or, if necessary, entirely new models could be developed.

Finally, it should be noted that serious problems exist, with respect both to “validation” of existing models and to the comparability of the results obtained from them. With respect to the former, most validations against actual field data have been performed either for only the simplest measures of performance (i.e., flow rates past certain waypoints) or under “mild” operating conditions. Few validation tests have been performed under conditions when airports/airspace operations are severely strained, for example when aircraft delays are of the order of one hour or more. The basic reason for this is that field data in such cases tend to be seriously “contaminated”, e.g., it is difficult to identify what delays are due to what causes; many flights may also be canceled or postponed under such circumstances, thus altering the initial capacity/demand relationships assumed by the models. As to the problem of comparability of results, there have been very few instances when two or more different models were tested with exactly the same data sets. Different models also “massage” input data differently and may use different aircraft performance datasets (for the same aircraft type) thus further complicating the task of comparing results of different models.

### 2.1.5 Recommended Model Toolkit

Table 2.2 shows a recommended toolkit of capacity and delay models which can be put together in the short run, after only relatively limited additional model development effort. As indicated the toolkit should include one or more models at each different level of detail. The “contents” of this toolkit could be modified in the future, as the outcome of several other ongoing model development efforts becomes more clear.

**Table 2.2: Recommended “Toolkit” of Analytical and Fast-Time Simulation Models of Capacity and Delays**

Level of Detail (type of study)	Scope of Model			
	Aprons and taxiways	Runways and final approaches	Terminal area airspace	En route airspace
Macroscopic		Enhanced Airfield Capacity Model* DELAYS*		
Mesoscopic		NASPAC or FLOWSIM		
Microscopic	T A A M or SIMMOD (airport)+ RAMS (airspace)			

The first macroscopic model in the toolkit is an analytical Enhanced Airfield Capacity Model that combines the best features of the LMI Runway Capacity Model with those of the FAA Airfield Capacity Model. Such a model, we believe can be developed quite easily and quickly. The second model is DELAYS which estimates efficiently airport delays based on the

airport's demand profile and its capacity. The latter can be an externally specified input or can be computed by the Enhanced Airfield Capacity Model described above.

We have not included AND in the toolkit, because it would be premature to do so before more experience is gained with this model. The same is the case with all the macroscopic en route airspace models listed in Table 2.1.

The mesoscopic models listed in Table 2.2 (NASPAC or FLOWSIM) are recommended --with reservations, for the reasons mentioned in Section 2.3 above. Both have deficiencies at this point and may soon be superseded by better versions of FLOWSIM or extensions/spin-offs of NASPAC or by TMAC and ASCENT --when development of these two models approaches its final stage. For environments where serious en route delays, in addition to airport delays, are encountered, NASPAC is the choice over FLOWSIM, TMAC and ASCENT, because of the significant emphasis that NASPAC places on the en route environment.

In the case of microscopic models, the airport portion of SIMMOD (the workstation version is strongly recommended over the PC version) is a viable, and in some respects superior, alternative to TAAM. A similar statement can be made about RAMS vs. TAAM, when it comes to airspace simulations. Thus, a combination of the airport portion of SIMMOD with RAMS may provide an alternative that offers an overall scope comparable to TAAM's. An effort to interface seamlessly SIMMOD and RAMS in this manner (SIMMOD for airport surface, RAMS for airspace) is currently under way in Europe.

Finally, three *caveats* are in order with respect to the recommended toolkit of Table 2.2. First, there is no implication that the models shown in the toolkit are fully satisfactory. They simply represent some of the best choices under the current state of the art. Second, it should be emphasized that the toolkit is only a "snapshot" of the situation at this moment. With much ongoing work on capacity and delay modeling, better alternatives than the ones recommended may emerge in the near future. Finally, there is also no implication that the models shown in the Table are currently compatible with one another. In fact, they are not: in the current absence of interfaces among them, they must necessarily be used as separate models with all the extensive effort that this implies in preparing the requisite model inputs and processing the associated outputs.

### 2.1.6 Recommendations for Improvement

Numerous steps can and should be taken to improve the state of the art in airport and airspace capacity and delay modeling. They can be summarized as follows:

- (a) Better integration of existing models: A toolkit such as the one outlined in Section 6 above should be assembled. This effort will certainly also spur development of interfaces that would assist the combined use of different models, whenever natural "affinities" between such models exist. Two most obvious examples of this type are interfaces between: (i) an enhanced

version of the LMI Airport Capacity Model and DELAYS (so that the former would compute runway system capacities which would then be “fed” into the latter to compute associated delays); and (ii) the airport module of SIMMOD and RAMS, so that airport capacity and delays could impact airspace operations and vice versa.

(b) Development of common databases and utilities/tools: There is an urgent need to develop a set of common databases and of utilities/tools to support capacity and delay models. The common databases will facilitate use of the models and make their results directly comparable. The utilities/tools will address needs that arise consistently whenever such models are utilized. The most pressing requirements are for databases and utilities/tools in the following areas:

1. Performance data for different aircraft types;
2. Airport geometry and airspace configuration data;
3. “Standard day” scenarios, i.e., databases that contain complete data for selected days, such as detailed weather conditions at airports and airspace, airline schedules (including daily itineraries of individual aircraft), other traffic demands, delays recorded, etc.;
4. Traffic generation/simulation tools (to simulate future traffic demand and generate hypothetical future airline schedules, including daily itineraries of individual aircraft, under alternative assumptions about future conditions);
5. Weather generation/simulation tool (to generate statistically correct representations of airport weather, en route weather or regional weather).

(c) Short-term model enhancements: Several of the macroscopic and microscopic models reviewed can be significantly improved in the short term with modest to significant effort. Most mesoscopic models reviewed (NASPAC, TMAC and the Draper Testbed) are currently in various stages of transition and it is premature to recommend further modifications to them. Examples (listed in an order corresponding to the level of effort required) include:

1. Enhanced version of an analytical capacity model that combines the best features of the LMI Runway Capacity Model and the FAA Airfield Capacity Model;
2. Addition of various input and output features to AND;
3. Addition of more stochastic features and conflict resolution capabilities to TAAM;
4. Improved version of SIMMOD with emphasis on user interfaces, error diagnostics and facilitation of scenario preparation.

(d) Medium- and long-term model development: Existing models will undoubtedly be succeeded by new and better models in the future. The

principal distinguishing feature of these models, compared to existing ones, will probably not be any major changes in their internal logic, but rather the application of advanced software engineering technology that would improve usability and robustness and reduce the cost of model-supported studies. The process of future model development would be greatly facilitated by the detailed specification of user requirements. Such specifications should be prepared with broad participation from the user community, so that the interests of civil aviation authorities, all types of aircraft operators, large and small airports, etc. will be taken into account. Model specifications should not be limited to microscopic models, but should also address user needs for macroscopic and mesoscopic models as well.

Another desirable feature of future models would be a set of diagnostic and optimization capabilities (see Section 6 above).

## 2.2 Model Reviews

### 2.2.1 LMI Runway Capacity Model

(5/6/96 ARO)

#### 1. Primary Model Category:

Runway system capacity.

#### 2. Summary:

The LMI Capacity Model is a generalized analytical and stochastic model for computing the capacity of a runway system. Its fundamental building block is a model that computes the capacity of a single runway, when the runway is used for arrivals only or for departures only or for mixed operations (arrivals and departures).

A key feature of the LMI model is that it attempts to take into account explicitly probabilistic aspects of airport operations. So, for example, the approach speeds, the runway occupancy times and the delay in communication time between airport controllers and pilots are all incorporated into the model as random variables. Another important feature is that the model takes a "controller-based view" of operations. In this respect, it calculates the spacing between aircraft as they enter the common approach path such that, with reasonable confidence, no violations will occur later.

The LMI Capacity Model is designed to compute the so-called "runway capacity curve", i.e., the set of points that define the envelope of the maximum throughput capacities that can be achieved at a single runway, under the entire range of possible arrival and departure mixes. Specifically, the model determines four points on the runway capacity curve. By interpolating between pairs of points with straight-line segments, one can then obtain (approximately) the full runway capacity curve. The four points are the following:

**Point 1:** The "all arrivals" point, i.e., the capacity of the runway when it is used for arrivals only.

**Point 2:** The "freely inserted departures" point which has the same arrival capacity as Point 1 and a capacity for departures equal to the number of departures that can be inserted into the arrival stream "for free", i.e., by exploiting large interarrival gaps without increasing the separations between successive arrivals (and, thus, without reducing the number of arrivals from what can be achieved in the all-arrivals case).

**Point 3:** The "alternating arrivals and departures" point, i.e., the point at which an equal number of departures and arrivals is performed. This is achieved through an arrival-departure-arrival-departure-... sequencing, implemented by "stretching", when necessary, the interarrival gaps, so that a departure can always be inserted between two successive arrivals.

**Point 4:** The "all departures" point, i.e., the capacity of the runway when it is used for departures only.

The LMI Capacity Model is still in its early stages of development and work on extending it to more than one runway is only beginning. (The version reviewed here is the one described in a draft report published in December 1995 -- see Section 12 below.)

### **3. Input Requirements:**

Input parameters to the model include: the mix and number of aircraft types at the runway ( $p_i$ ); the length of the common approach path ( $D$ ); the mean and standard deviation of the approach speed of each aircraft type [ $V_i$ ,  $sd(V_i)$ ]; the mean and standard deviation of the arrival and departure runway occupancy times [ $RA_i$ ,  $sd(RA_i)$ ,  $RD_i$ ,  $sd(RD_i)$ ]; the miles-in-trail separation minima for all pairs ( $i,j$ ) of aircraft types ( $S_{ij}$ ); the standard deviation of wind speed encountered by aircraft  $i$  on final approach [ $sd(W_i)$ ]; the uncertainty in the position of aircraft  $i$ , quantified by the standard deviation,  $sd(X_i)$  of its location,  $X_i$ , along the final approach; and the mean and standard deviation of the communication time delay [ $c$ ,  $sd(c)$ ]. For departures, the model also uses the mean and standard deviation of the departure speed for each aircraft class and the minimum distance that departing aircraft must fly before turning. All the input random variables are approximated as normally distributed to facilitate the derivation of approximate expressions for the expected values and standard deviations of parameters of interest.

### **4. Outputs:**

Capacity of a single runway for the four operating conditions (Points 1, 2, 3 and 4) described in Section 2 above. Capacity is defined here as the number of operations that can be carried out on a runway with 95% confidence in the presence of continuous demand. (Note that, although related, this definition is different from the usual definition of "maximum throughput capacity"; the latter is simply the expected number of operations that can be carried out in the presence of continuous demand.)

### **5. Major Assumptions:**

As noted, the LMI capacity model assumes, for computational purposes that all its input variables are normally distributed with known expected values and standard deviations. The model also uses a new definition of capacity ("the number of operations that can be carried out in one hour with 95% confidence"). The model assumes that the "double occupancy rule" (two landing aircraft should not be on the same runway at the same time) should be maintained 98.7% of the time.

### **6. Computational Characteristics:**

The LMI Capacity Model runs on a PC and requires no significant computational features. Versions of the single runway model have been prepared in both Pascal and C. The Pascal code is given in Appendix A of the document referenced in Section 12 below. The model uses a GUI, in the form of a Lotus spreadsheet, which allows the user to enter the model's

input parameters and displays the capacity curve implied by the current parameters, as well as the curve implied by a set of reference parameters.

#### **7. Modularity and Flexibility:**

The LMI Capacity Model is very easy to use and can potentially be incorporated as a module into models of more extensive scope, such as a model that would compute not only airport capacity, but also airport delays.

#### **8. Status of Model:**

The LMI Model has been developed only recently. A generalized model exists only for single-runway operations. Applications that extend the model in an ad hoc way to multiple runway operations have been carried out for the Detroit and Boston Logan airports.

#### **9. Extent of Model Validation:**

The single runway model has been partially validated through comparison of its results with those of the FAA Airfield Capacity Model. The ad hoc extensions to multiple runway operations (see Section 8 above) have been validated through comparisons with the capacities actually achieved at the Detroit and Boston Logan airports.

#### **10. Principal Applications:**

The LMI Capacity Model is currently being used in connection with the evaluation of the potential benefits of the NASA Terminal Area Productivity (TAP) Program.

#### **11. Model Availability:**

Arrangements for obtaining the code for the LMI Capacity Model can be made by contacting Dr. David A. Lee [dlee@mail2.lmi.org, (703) 917-7557] or Dr. Peter F. Kostiuk [pkostiuk@lmi.org, (703) 917-7427].

#### **12. Information Base for Model Evaluation:**

Brief discussions with Dr. Peter F. Kostiuk and Dr. David A. Lee.

Report:

Earl W. Wingrove, David A. Lee, Peter F. Kostiuk, Robert V. Hemm, Estimating the Effects of the Terminal Area Productivity Program, Logistics Management Institute, McLean, VA.

#### **13. Summary Evaluation:**

The LMI Capacity Model is still not fully developed; it currently consists of a single runway model only with some ad hoc extensions to configurations with multiple runways. A more definitive evaluation of the model must therefore wait until completion of model development. However, the work done to date is very promising. The exposition of the single runway model is rigorous and the model's assumptions are clearly stated and explained. The model constitutes the first attempt after many years to develop another

analytical model of a probabilistic nature that would approximate well airport capacity under a wide variety of conditions. Its results, for the cases to which it has been applied to date are close to those observed in the field.

A technical aspect that may require improvement in the future is the logic for inserting departures between arrivals on the same runway: for example, the model does not currently include a minimum distance separation between a departure and the following arrival at the time when the departure is set to begin its take-off roll; the model may also be inserting too many "free" departures between arrivals under certain conditions. The definition of capacity as "the number of operations that can be carried out in one hour with 95% confidence" is also unconventional and may result in lower estimates of capacity than those obtained under "the maximum throughput rate" definition of capacity. However, the LMI Capacity Model can be easily adjusted to provide estimates consistent with the "maximum throughput rate" definition.

### **2.2.2 FAA Airfield Capacity Model**

(ARO; 7/29/96)

#### **1. Model Category**

Airport Capacity.

#### **2. Summary**

The FAA Airfield Capacity Model is an analytic computer model which calculates the (maximum throughput) capacity of a runway system given continuous demand. Given data on the runway configuration and operating procedures in use, it estimates the hourly capacity for 15 common airfield configurations ranging from a single active runway to four active runways. The model was initially developed in the late 1970s by a consortium that included Peat, Marwick, Mitchell and Company and McDonnell Douglas Automation and further modified by the FAA with support from the MITRE Corporation. It was last modified in February 1981.

The model approximates single runway capacity using logic based on the fundamental concepts of the classical Blumstein model and its extensions. For more complex configurations it uses modules (models) that extend the analysis. Combinations of these base modules are then used for even more complex configurations.

#### **3. Inputs**

The input is a single text file with information on: runway configuration in use and the type of operations (arrivals, departures or both) assigned to each runway; aircraft mix on each runway; ATC separation requirements between operations on each runway; aircraft characteristics, such as final approach speed, runway occupancy times for arrivals and departures; length of final approaches; and weather inputs (ceiling and visibility) to determine flight rule conditions. Standard deviations of those inputs which are treated as random variables (e.g., runway occupancy times) are also required.

#### **4. Output**

The model estimates the capacity per hour of the runway system for any specified arrival-departure ratio. Increments of 10% are used, if desired, to obtain a capacity "envelope" that consists of 11 points ranging from (100% arrivals, 0% departures) to (0% arrivals, 100% departures).

#### **5. Major Assumptions**

The FAA Airfield Capacity Model assumes that each of the 15 common configurations it can analyze can be viewed as a combination of four fundamental configurations: single runway, closely-spaced parallel runways, intermediate-spaced parallel runways and intersecting runways. For each of these four fundamental configurations it includes a module which computes that configuration's capacity. These modules are, in turn, based on a single-runway model that computes (i) the "all arrivals" capacity of the runway, (ii) the "all departures" capacity and (iii) the capacity of the runway when departures are inserted between arrivals, without reducing arrival capacity. The capacity for other mixes of arrivals and departures is then computed by interpolating among these three points.

All random variables in the model are assumed to be normally distributed and a 5% probability of violation of separation requirements is used in determining spacing of runway operations, using these normal distributions.

An implicit assumption is that taxiways and gates have little impact on determining airfield capacity. Another implicit assumption is that many airports operate with one of the fifteen runway configurations that the model analyzes and therefore the model will be useful. Both of these assumptions are substantially true in practice.

#### **6. Computational Characteristics**

The code is written in FORTRAN and is available for IBM machines, running on just 200 KB of memory. The User's Guide contains a full description of the methodology used and clear instructions on how to run the program. Provided that the relevant information is available, it takes little time to prepare the input file and run the program. No graphical interface is available.

#### **7. Modularity and Flexibility**

Almost all variables are specified by the user, so the model can handle most situations. Since the output is a simple number, using the FAA Airfield Capacity Model in combination with other software packages is straightforward.

#### **8. Status of Model**

This is considered a "mature" model, with no changes planned.

## **9. Extent of Model Validation**

Model validation took place in the 1970s. For selected configurations and cases, it was determined that the model provides adequately accurate estimates of airfield capacity.

## **10. Principal Applications**

The model was used in the preparation of the FAA Handbook of Airport Capacity and Delay in 19(??). It has also been used in connection with a number of airport studies in the late 1970s and early 1980s, but its use seems to be limited today.

## **11. Model Availability**

The FAA Airfield Capacity Model can be obtained from

William J. Swedish,  
CAASD  
The Mitre Corporation,  
7525 Colshire Drive,  
McLean, Virginia 22102.

## **12. Information Base for Model Evaluation**

The model was obtained and exercised at MIT. The following report was also reviewed:

Upgraded FAA Airfield Capacity Model Supplemental User's Guide, William J. Swedish, The Mitre Corporation, McLean, Virginia 22102, February 1981.

## **13. Summary Evaluation**

The FAA Airfield Capacity Model can be a useful tool for policy-level studies that require quick approximate estimates of the sensitivity of airfield capacity to various changes in the most common operating parameters of airports (number and configuration of runways, aircraft mix, separation requirements, runway occupancy times, etc.) The model, however, can be improved significantly, particularly with respect to the logic for inserting departures between two arrivals on a runway. Because the model's logic is not particularly good in this respect, the model's estimates of capacity for cases in which a runway handles approximately the same numbers of arrivals and departures will often not be particularly accurate. The FAA Airfield Capacity Model could also be strengthened by including in it some of the features that exist in the single-runway analytical capacity model that was developed recently by LMI (see review in this volume). In fact, a new model that combines the single-runway logic of the LMI model with the extension to multiple runways featured in the FAA Airfield Capacity Model could be a very useful tool that would provide instantaneous estimates of runway system capacity with limited data requirements.

### 2.2.3 AND: Approximate Network Delays

(ARO; 7/15/96)

#### 1. Primary Model Category:

System-wide model of airport delays

#### 2. Summary:

AND (Approximate Network Delays) is a network queueing model developed at the MIT Operations Research Center, with software development support and database provided by the MITRE Corporation. Its objective is to analyze the impact of changes in airline schedules, traffic volume and airport capacity on flight delays on a national or regional basis. AND is an analytical tool and uses the DELAYS model as its engine for solving the differential equations that describe the distribution of delays over a network of airports, given flight schedules, aircraft itineraries and airport capacities. AND currently includes a database that encompasses the 58 busiest airports in the United States and can thus be used to estimate, on a national scale, the benefits and costs of local or regional changes in airport infrastructure and in terminal area ATM technologies and procedures.

#### 3. Input Requirements:

The inputs required by AND are:

1. The capacity profile of each of the airports of interest for the period of interest. (The typical period of interest in AND is one full day of network operations.) This capacity profile can be dynamic, i.e., the capacity may change at specified intervals of time. For example, if the period of interest is one day (midnight to midnight) and if the time interval specified is one hour, the capacity profile of each of the airports in the network is specified by an array of 24 numbers, the first number giving the airports capacity from midnight to 1 a.m., the second from 1 a.m. to 2 a.m., etc.
2. The demand profile for arrivals and for departures at each of the airports of interest for the period of interest. The demand profiles are specified in exactly the same way as the capacity profiles (see above) and thus can be dynamic.
3. A complete schedule of flights that must be performed during the period of interest in the airport network of interest and the itineraries of each of the aircraft which will perform this schedule. For example, if Flight 123 by airline XYZ will begin from Airport A and then visit successively Airports B and C, before it terminates at D, the scheduled times of departure from A, arrival and departure at B and C and arrival at D must be provided. If, moreover, the aircraft that performed flight 123 will, after its arrival at D, be assigned to perform Flight 456, scheduled to depart from D at a later time, this also has to be indicated in the set of inputs to AND. (In the absence of data on aircraft itineraries, the AND model can be preceded by a pre-processor, prepared by the

MITRE Corporation, which processes airline schedules to infer such itineraries.)

#### 4. Outputs:

The principal quantity computed by AND is the probability vectors

$P(i, t, k)$  that  $i$  aircraft will be in queue (waiting to land or to take-off) at time  $t$  at airport  $k$ . The values of these probability vectors are computed for all values of  $i$  ( $i = 0, 1, 2, \dots$ ) at time  $t$ , for  $t = 0, \Delta t, 2 \Delta t, 3 \Delta t, \dots$  up to the end of the time period of interest for all the airports in the network. Using the  $P(i, t, k)$ , AND then computes derivative measures of performance such as:

- the expected queue length at each airport as a function of time;
- the expected waiting time for operations at each airport as a function of time;
- the total delay suffered by aircraft during the entire period of interest at each airport;
- the fraction of aircraft delayed at each airport by more than  $X$  minutes (e.g., 15 minutes) during the period of interest, where  $X$  is a user-specified value; --the part of the expected delay at each airport that can be attributed to local congestion and the part which is attributed to "upstream" delays, i.e., to congestion at airports visited earlier in the day.

#### 5 Major Assumptions:

The AND model makes two fundamental assumptions: First, it does not deal at all with delay due to en route airspace congestion, assuming implicitly that the great majority of delays in the ATM system is due to airport and terminal area congestion. This assumption is true in certain ATM environments (such as the United States) but false in others (e.g., in Western Europe, where a substantial amount of air traffic delay is caused by lack of en route sector capacity).

Second, AND assumes that airports in the network under study are "weakly connected" meaning that no airport receives more than approximately 25% of its flights from any other single airport. This condition is necessary if the methodology used by AND is to be valid (see Reference (2) under item 12 below) and is indeed true for practically all major commercial airports in the world.

AND makes no distinction between arrivals and departures and treats all airport operations as demands that are served according to a first-come, first-served queue discipline. However, the effects of variations in the traffic mix (e.g., a high percent of arrivals during any particular hour) can be captured by adjusting accordingly the capacity of airports to reflect these variations.

Two additional assumptions of a more technical nature are due to the use of the DELAYS model (see review of DELAYS) as the "engine" of AND. Specifically, it is assumed that: demand at each airport can be approximated by a non-homogeneous Poisson process (i.e., demands occur at random instants with a demand rate that varies over time); and the service time per operation can be approximated by a k-th order Erlang random variable, with expected value (which may change over time) and standard deviation equal, respectively, to the corresponding (observed or estimated) expected service time and standard deviation of service time at the airport. (The appropriate order, k, of the Erlang random variable is determined by the relative magnitude of the expected service time and standard deviation of service time.)

Finally, in propagating delays through the network of airports, AND assumes that the delay suffered by each airport operation is equal to the expected value of the delay at the time when that operation is scheduled to take place. (For further discussion, see References (1) and (2) under item 12 below.)

## **6. Computational Characteristics:**

AND is currently implemented in two versions, a serial model and a parallel model, both of which run on SUN SPARCstation 10 workstations. The parallel version exploits networks of workstations to speed up model execution by a factor of approximately 2. A typical execution time for a run involving a complete day of operations (about 50,000 landings and take-offs) at the 58 principal commercial airports in the United States takes approximately 20 minutes on the serial version (and approximately 10 on the parallel).

AND runs with a mouse-driven GUI, through which the user can select different scenarios for execution, create new scenarios or modify existing ones. An Editor is included with the GUI to facilitate the modification of the capacity profiles of the airports in the network, if desired. A map display facilitates the selection of airports to be included in the network being studied.

## **7. Modularity and Flexibility:**

The AND model is modularly designed in the sense that the DELAYS model which serves as AND's "engine" can be easily replaced, if desired, by another model that computes delays at any given airport. The number of airports in the network can be easily adjusted and can range from 2 to 58, at this point.

## **8. Status of Model:**

The current version of AND is a fully-developed working prototype that, while containing all the fundamental eventual capabilities of the model, can still be significantly improved through the addition of several significant features that would enhance its applicability. A plan for such improvements exists.

## **9. Extent of Model Validation:**

A comparison has been conducted at MITRE between the results of the AND model and those of NASPAC. A set of tests involving a network containing many of the busiest airports in the United States, indicates that when NASPAC is used with all its features, NASPAC and AND give very similar results.

## **10. Principal applications:**

The AND model is still an experimental tool and has not been used to date in specific applications.

## **11. Model Availability:**

The model is not transportable at this point. Arrangements for its use can be made either through MIT (Professor Amedeo R. Odoni, Room 33-404, MIT, Cambridge, MA 02139, USA [(617) 253-7439, fax: (617) 253-7397; odoni@mit.edu]) or through MITRE (Dr. Andrew Haines, CAASD, The MITRE Corporation, 7525 Colshire Drive, McLean VA 22102, USA [(703) 883-6714; haines@mitre.org]).

## **12. Information Base for Model Evaluation:**

The following documents describe the logic of the AND model:

1. Malone, Kerry (1993) Modeling a network of queues under nonstationary and stochastic conditions, S.M. Thesis, Operations Research Center, Massachusetts Institute of Technology, Cambridge, MA.
2. Malone, Kerry (1995) Dynamic queueing systems: behavior and approximations for individual queues and networks, Ph.D. thesis, Operations Research Center, Massachusetts Institute of Technology, Cambridge, MA.

## **13. Summary Evaluation:**

The AND model is the first analytically-based (not simulation) model that provides a fast, and flexible tool for delay analysis in a network of airports. It is designed for supporting policy analyses that require approximate estimates of system performance under a broad range of alternative assumptions. Because it is an analytical model (and thus requires but a single run to compute the probability distribution of flight delays for any given set of capacity and demand conditions) AND can outperform considerably, in terms of computational efficiency, existing national-scale simulation models in addressing issues related to the propagation of delays in the system of airports and to the national or regional delay impacts of changes in airline schedules, in airport demand levels and in airport capacities. The model is macroscopic and reflects the dynamic and stochastic nature of ATM/airport operations.

The model disregards completely delays which are due to congestion of en route airspace and it is thus more appropriate for ATM environments (such as the United States) where the great majority of air traffic delays is associated with airport congestion. AND also cannot capture the impact on the distribution of delays among airport users of air traffic control strategies that would assign priorities to certain types of operations (e.g., arrivals) over others (e.g., departures). It can, however, estimate the aggregate effects of such strategies.

The model is still an experimental tool, as it is not transportable and lacks a number of desirable features that would facilitate its use and the preparation of certain of its inputs. If these features were added, AND would constitute a very competitive alternative to system-wide simulation models, such as NASPAC and FLOWSIM, for many types of policy-level studies.

#### **2.2.4 THE AIRPORT MACHINE**

Model Review (EMF 10/96, ARO 7/96)

##### **1. Primary Model Category**

Airport capacity and delays.

##### **2. Summary**

The Airport Machine is a tool for simulating in detail all aspects of airfield operations (including runways, taxiways and apron areas). Its principal measures of performance (and outputs) are flows and throughput capacity on the airfield per unit of time, and delays experienced at the various airfield facilities. It is based on a node-link structure similar to that of SIMMOD, and covers all aircraft activities from a few minutes before landing until a few minutes after take-off. This commercial software package was developed by Airport Simulation International (ASI).

The Airport Machine relies on high-level-of-detail network representations of airfields. Traffic moves along a network of links and nodes with each link being able to accommodate a single aircraft at a time. Whenever two aircraft converge on the same link, the operating strategies programmed into the model determine which of the two candidates will occupy that link first and which will incur delay.

Competing models include TAAM, SIMMOD and HERMES.

##### **3. Input Requirements**

The airport under study needs to be entered into the tool as a node-link network. Other inputs include schedule files, airport structure and ATC procedures. Aircraft types and wind information can also be model inputs. Up to eight aircraft types (user defined) and their characteristics can be specified. Control actions may either be entered manually in real time, as the simulation is being performed, or coded as a rule-base to be executed automatically.

#### **4. Outputs**

The Airport Machine is equipped with a good graphical interface which is very useful for model calibration and validation purposes. The post-processor computes flows and delays at specific locations, identifies potential bottlenecks, and produces flow/delay graphs.

Examples of information available include: numbers for arrival and departures for specified periods of time; gate occupancy times; statistics on towing operations; number of occupied gate positions; number of aircraft in the various airport queues.

#### **5. Major Assumptions**

The Airport Machine assumes a node-link structure for aircraft operations. It begins simulating operations as arriving aircraft reach the outer marker and stops immediately after take-off. It assumes that take-off operations are independent from the eventual route taken by the aircraft past the fix, so that no airborne trajectory is shown. This has been reported as a problem in some cases.

The Airport Machine can perform only single-airport studies. The flight schedule includes information about flight routes, aircraft class and parking positions. Average taxi time is "minimized" by default by The Airport Machine.

#### **6. Computational Characteristics**

The Airport Machine runs on a standard PC (MS-DOS) plus a graphics card. Two screens are necessary, one for text editing and one for graphics display. Memory requirements are 4Mb of RAM. The source code is not provided. The code was originally written in Pascal.

The support and documentation are both reportedly very good.

A typical run time for a major and very busy airport takes about 10 minutes for 24 hours of traffic.

The startup effort is about 2 to 4 weeks for people with prior exposure to simulation tools. The user interface is reportedly very good.

#### **7. Modularity and Flexibility**

The Airport Machine is a closed-architecture software system. An object oriented version is planned for future release.

#### **8. Status of Model**

Mature.

## **9. Extent of Model Validation**

The model has been used in numerous airport studies by now and can be considered validated under a wide range of conditions. Users report good agreement of model outputs with field observations.

## **10. Principal Applications**

Numerous applications at many airports in the United States and Europe. For instance, the model was used recently in studies of alternative strategies for increasing capacity at Boston and Frankfurt airports.

## **11. Model Availability**

The Airport Machine is available from Airport Simulation International, Inc.. The Airport Machine is licensed to users on an airport-by-airport basis. The price is about \$20K for the first license and about \$10K for each additional airport. Contact Airport Simulation International, Huntington, NY 11743, USA.

## **12. Information Base for Model Evaluation**

Interview on January 9, 1996 with:  
Ingrid Gerdes, (49) 531 295 2279, (ingrid.gerdes@dlr.de), and Franz Knabe, (49) 531 295 2496, (fl1g@brzsp7.bs.dlr.de), both from DLR.

Discussions with Dr. Joline

Discussions with several model users.

## **13. Summary Evaluation**

The Airport Machine is a commercial product to evaluate airport capacity and delays. It is intended to support detailed design-level studies, offering "fine granularity" simulation of airport surface operations. It is a mature, quite user-friendly software package that has been used extensively and whose results have been validated. Users must undergo a significant amount of training and the cost of acquiring the model is considerably higher than that of SIMMOD. On the other hand, the current user interface of The Airport Machine is superior to that of SIMMOD.

### **2.2.5 SIMMOD**

(3/2/96; ARO)

#### **1. Primary Model Category:**

Airfield and terminal airspace models. Secondary area: en route and regional airspace models.

## 2. Summary:

SIMMOD can be used to simulate in detail: a full individual airfield (including runways, taxiways and apron areas); an airfield and its associated terminal airspace; a regional system of airports and the associated airspace; or, a regional volume of airspace. Its principal measures of performance (and outputs) are aircraft travel times, flows and throughput capacity per unit of time, delays and fuel consumption.

SIMMOD relies on high-level-of-detail network representations of airfields and airspace. Traffic moves along a network of links and nodes with each link or node (depending on whether airspace or airport surface operations are being modeled) being able to accommodate a single aircraft at a time. Whenever two aircraft converge on the same node or link, the operating strategies programmed into the model determine which of the two candidates will occupy that node or link first and which will incur delay. Aircraft paths on the network are either specified by the user for every origin-destination pair or determined internally by the model according to a shortest-path (Dijkstra) algorithm.

Much of the effort associated with setting up a SIMMOD simulation is, in fact, expended in developing the airspace and/or airfield network on which the traffic will move. For example, if a fan or trombone pattern is to be utilized to increase the efficiency of approach spacing and sequencing, all the possible alternative paths in the fan or trombone must be explicitly "programmed" as part of the network representation.

SIMMOD has several options for simulating probabilistic events and can provide highly detailed output statistics down to the individual aircraft level.

Competitive models are TAAM and, for airspace simulations only, RAMS.

## 3. Input Requirements:

The principal input requirements are the specification of the network structure for the airfield and/or airspace simulated and the description of the traffic that will move on this network, including flight paths and paths between gates and runways. To partially automate the tedious process of developing such networks, one can use a digitizer to trace the network of runways, taxiways and taxilanes from an airport layout map. Such an approach reportedly reduces the amount of time necessary to set up a network representation for a typical major airport to approximately 2 days of effort. It is also possible to use flight plans to generate the route network on which a SIMMOD airspace simulation will be based. SIMMOD includes a database with performance characteristics for 19 types of aircraft. A recently-added SIMMOD capability developed by Virginia Polytechnic Institute & State University (Virginia Tech) checks the network specifications of airfields provided by the user to ascertain conformance with FAA standards for separations between runway/taxiway and taxiway/taxiway centerlines, runway exit curvatures, etc.

#### **4. Outputs:**

SIMMOD provides highly detailed statistics on each aircraft simulated. Outputs can be obtained on: aircraft travel times; traffic flows past specified points; throughput capacity per unit of time; delays by time of day and location on the airfield or in airspace, along with the immediate reason for each delay; and fuel consumption.

#### **5 Major Assumptions:**

The principal restrictive assumption in SIMMOD is that traffic must move on a pre-specified network of nodes and links according to pre-specified operating strategies or "rules of the road". In terms of conflicts between aircraft paths, SIMMOD is essentially a 1-dimensional model, checking for conflicts along the aircraft's longitudinal path only, with no possibility of checking for lateral or vertical separation violations.

#### **6. Computational Characteristics:**

SIMMOD is written in SIMSCRIPT II.5 with a pre-processor and post-processor in C. It can be run on a personal computer, but for large applications a workstation (Sun or HP) is recommended. A 500 MB hard drive is required as well as a tape drive. Operating system: Unix or DOS. The SIMMOD software includes the HOOPS graphics card.

As an indication of speed of execution, a simulation of 24 hours of operation at a major airport takes about 3-5 minutes (single run).

#### **7. Modularity and Flexibility:**

Ongoing efforts at Eurocontrol and CAA are aiming at developing a data interface (SIMBUS) so that RAMS and SIMMOD can be operated serially, with RAMS bringing aircraft to the final approach and SIMMOD picking them up there to simulate airport operations (and conversely for departing aircraft). Another area of interest at CAA is the development of a capability to specify externally the operating strategy in use at an airport or section of airspace and have SIMMOD execute this strategy in simulating operations. Currently such strategies must be programmed as part of the logic of the model; changing them requires a major effort.

SIMMOD can be linked to the Integrated Noise Model (INM) so that the noise impacts of airport operations can be estimated.

#### **8. Status of Model:**

SIMMOD is a mature model, having undergone many revisions and improvements over a period of more than 15 years. Funding does not currently exist in the FAA for additional development of SIMMOD. The FAA recognizes the value of SIMMOD and is considering new funding methods to ensure SIMMOD's future growth and development. One proposed funding scenario involves bringing SIMMOD under the umbrella of the FAA's proposed Aviation Operations Research Center of Excellence (COE).

## **9. Extent of Model Validation:**

The ATAC Corporation conducted a validation study of SIMMOD in 1988 (see Bobick, J. C., "Validation of the SIMMOD Model," ATAC Corporation, Mountain View CA, Contract No. DTFA03-85-C- 00043). The ability of the model to provide realistic results under quite complex operating conditions has been confirmed repeatedly in a number of airport and airspace simulation studies.

## **10. Principal Applications:**

SIMMOD is possibly the most widely utilized airport and airspace model in the world today, with about 300 registered users worldwide, 50-100 of whom are believed to be currently active. The model has also been the beneficiary of significant support and promotion by the FAA over the past decade.

The great majority of applications to date have dealt with the capacity and delay impacts of a variety of operational alternatives at airports. More recently, several studies dealing with reconfiguring regional or terminal airspace to reduce delays, reduce fuel consumption or improve operational efficiency have also utilized SIMMOD.

## **11. Model Availability:**

SIMMOD is available at a nominal cost from the FAA (about \$1,500 for the workstation version, about \$400 for the PC version). Several companies in the United States (ATAC, CACI, SDT) offer training courses, typically one-week long, and/or provide software support for SIMMOD.

Contact persons in the FAA are Tony Vanchieri ((202) 358-5198, fax (202) 358-5543, [avanchieri@mail.hq.faa.gov](mailto:avanchieri@mail.hq.faa.gov)) and Steve Bradford ((202) 358-5234, [sbradford@mail.hq.faa.gov](mailto:sbradford@mail.hq.faa.gov)).

## **12. Information Base for Model Evaluation:**

Interview with Steve Bradford on 12/18/95.

Informal discussions with several users in the United States, Europe and Australia.

Review of a draft report (October 1995) by DLR on an extensive series of simulation experiments at Frankfurt airport and terminal airspace.

Review of the following documents: (i) Federal Aviation Administration, SIMMOD Data Input Manual, 1989; (ii) Federal Aviation Administration, SIMMOD Information Brief, 1989; (iii) Federal Aviation Administration, SIMMOD Reference Manual, Office of Operations Research (AOR-200) 1989.

## **13. Summary Evaluation:**

In the hands of a skilled user, SIMMOD is possibly the most powerful existing tool for "fine granularity" simulation of airport surface operations,

allowing for arbitrarily high levels of detail (e.g., simulation of push-back operations, gate occupancies, de-icing procedures, etc.). Several airport studies conducted with SIMMOD to date illustrate this point.

The principal perceived weakness of SIMMOD is that it is a "labor intensive" model whose users must undergo a significant amount of training. Moreover, to avoid several potential pitfalls, SIMMOD users must have a very good understanding of ATM and airport operations. For example, because SIMMOD is essentially a one-dimensional model (i.e., it can check for conflicts between aircraft only along the paths traced by the elements of a network) care must be taken so that the network structure on which the traffic moves is based on sets of nodes and links with sufficient lateral and vertical separations to avoid the presence of undetected conflicts during the simulation.

Another difficulty in SIMMOD is the modeling of dynamic rerouting of aircraft to simulate the ATM system's responses to local congestion problems.

In summary, especially when its low acquisition cost is considered, SIMMOD may be the model of choice for high-level-of-detail airport simulations, with TAAM the principal competitor. The model's steep "learning curve" should, however, be recognized. For airspace studies, both RAMS and TAAM may be better alternatives at this point. For the specific case of evaluating the Free Flight concept in en route, transitional and terminal area airspace, an important limitation is the pre-specified underlying network structure on which traffic is restricted to move in the SIMMOD model.

## **2.2.6 TAAM: Total Airspace & Airport Modeller**

(5/14/96, KK)

### **1. Primary Model Category**

Full Air Traffic system simulation.

### **2. Summary**

TAAM (Total Airspace & Airport Modeller) is a large scale detailed fast-time simulation package for modeling entire air traffic systems, developed by The Preston Group (TPG) in cooperation with the Australian Civil Aviation Authority (CAA).

TAAM can be used as a planning tool or to conduct analysis and feasibility studies of ATM concepts. TAAM can simulate most ATM functions in detail and can provide scenario generation for real-time ATC simulators. The simulations cover the entire gate to gate ATM process, generally in more detail than competing models.

A TAAM simulation consists of a collection of user provided data relevant to the problem at hand and its modeling requirements. TAAM takes as input the air traffic schedule, environment description, aircraft flight plans, air

traffic control and output control rules. It uses them in performing airport and airspace usage, conflict detection and resolution, and aggregate metrics calculations with its internal algorithms and user defined rulebases.

TAAM modules include an interactive graphical fast-time simulation tool which provides the user with a 2D or 3D view of the airspace or airport; a real-time air traffic monitoring tool with simulation capability; and a reporting tool which can be used to generate graphs and tables from data generated by the simulation. Simulations can be interrupted and restarted and key aspects of the model, such as conflict resolution and airport resource usage are controlled by rulebases which may be edited by the user during a simulation run. 'Live' graphical display of the simulation can be selected and customizable reporting is available. The simulation can also be run unattended in batch mode, with no graphics. During the simulation, statistics are gathered by the reporting program and written to a report file. This file is used by the Report Presentation Facility to construct the text and graphical reports desired by the user.

Competing models: ASIM, SIMMOD, RAMS.

### **3. Input Requirements**

As TAAM is a large scale simulation of an Air Traffic system, comprehensive input data files describing the entire Air Traffic system are needed. The level of detail can be varied for better modeling of critical areas. The inputs are the following:

- Airport Descriptions
- Airspace Route and Sector Layouts
- Geographical Features
- Air Traffic Control Rules
- Airport Usage Rules
  - wake turbulence and other standards
  - SIDs/STARs/route selections etc.
- Traffic Timetables
- Aircraft Trajectories and Routes
- Aircraft Performance Characteristics
- Conflict Detection and Resolution strategies

Default input files for a large proportion of these are available. Most data entry for building the environment model and operation rules is interactive, and various data entry tools are available:

- 2D/3D graphical editor (CAD tool) for entering and editing graphical data such as airport layouts, airspace sectors, etc.
- Data entry and validation tool for entering and maintaining data such as waypoints, routes, etc.

Other data entry tools e.g. a digitizer for digitizing paper maps, and an external data converter for importing maps in AutoCAD(TM) format and Jeppesen(TM) data.

#### **4. Outputs**

These are in general aggregated metrics and can be reported on system or sector wide basis.

- System delays
- Conflicts: counts by degree of severity, whether successfully resolved or not
- Airport movements, delays, operations on taxiways and runways, runway occupancy
- Airspace operation metrics such as usage of routes, sectors, fixes and coordination
- Noise contours
- Total fuel burnt
- Costs: aggregate, fuel, non-fuel
- Controller workloads
- Individual Aircraft flight profiles
- Scenario generation e.g. for real-time ATC simulators or other playback
- "Show Logic" diagnostics which gives the operator an insight into TAAM's decision making process
- Text messages (extent and content user selectable) which contain further details of TAAM events
- Errors

A 2D or 3D graphical visualization of the simulation can also be generated. The graphical output can be viewed in several windows simultaneously, each window having an independent 2D or 3D view with the scale ranging from 30 m to 40,000 km.

#### **5. Major Assumptions, Limitations**

Hazardous weather, or special use airspace cannot yet be modeled dynamically. Weather modeling was limited to winds aloft in sectors, but according to TPG the user can now input SIGMETs (severe weather advisories) and TAAM can determine which aircraft, and when, will be affected by these severe weather areas. Conflict detection and resolution is selectable but may not resolve all conflicts.

#### **6. Computational Characteristics**

Hardware: Sun SPARCstation 20, 75Mhz cpu with 288MB memory and two 1.05GB hard-disks. Minimum requirements depend on the size of simulation to be run. Speed of simulation is strongly dependent on the scale (flights/day) and computation time varies approximately with the square of

the number of aircraft(real + ghost) in the simulation. Depending on the hardware used and the options enabled, TAAM can simulate airspaces up to the size of the entire continental United States. On the machine described above, a 16,000 flights for a day simulation takes about 24 hours to complete. Capacity improvements continue to be made.

TPG quotes the following benchmarks for the latest TAAM version:

- 20,000 flights a day, conflict detection/resolution enabled: 17 hours on a typical SPARC20.
- 35,000 flights a day, conflict detection/resolution disabled: less than 4 hours on the same machine.

Graphical visualization is available. The user can switch between 2D and 3D mode at will, and has full control over the view. Simulation runs can be seen from any angle, from 'God's eye' view to 'worm's eye' view. Zoom is continuous from looking at the whole world to a single aircraft, with any stage in-between. Screen dumps can be made of any view. The simulation can also be run unattended, with no graphics. The user has full control over the simulation; he can at any time stop the simulation, make changes to airport operation or various aspects of the airspace, and restart the simulation.

## **7. Modularity and Flexibility**

TAAM is available as an executable with customizable input and output files. Rulebases of most aspects are reconfigurable and can be edited even during simulation runs. Linking with other programs is possible via input and output files. Additional packages allow linking with other ATM programs such as the FAA's Integrated Noise Model.

## **8. Status**

Version 2.x of TAAM is available with a number of optional modules. Additionally, TAAM is available as TAAM Airport, TAAM TMA, and TAAM Enroute, with reduced range and functionality.

## **9. Extent of Model Verification**

Comparisons with FAA studies on some aspects of new ATM concepts have been performed showing comparable results. The simulation model has been verified by many users on a variety of scenarios. Aircraft movement in 4 dimensions can be fine tuned to get within 3%-4% of actual aircraft profiles. The same accuracy can be obtained for airport movement rates and other characteristics.

## **10. Principal Applications**

Complete system simulation of present and proposed ATM systems and concepts. For example comparison between system performance using ATC preferred routes and Great Circle routes.

TAAM has a broad user base and many studies have been conducted many over the last 4-5 years, ranging from adding a couple of gates to designing London TMA procedures to total redesign of national airspace.

The principal areas of application have been:

- Airport capacity (gate, taxiway, runway capacity)
- Planning airport improvements, extensions
- De-icing
- Noise impact
- Impact of severe weather
- Design of terminal area procedures (SIDs/STARs)
- Design of terminal area ATC sectors
- Controller workload assessment
- Impact of new ATC rules, e.g. reduced vertical separation
- Systemwide delays
- Cost/benefit studies

## **11. Availability**

The software is available from:

The Preston Group Pty Ltd.  
488 Victoria St.  
Richmond, VIC 3121,  
Australia

## **12. Information for Model Evaluation**

Datta, K. and G. Schultz, "An Evaluation of TAAM for Free Flight Modeling", Draft Report, Sverdrup Technology Inc., NASA Ames Research Center Moffet Field CA 94035

Hank Wojcicki; TAAM homepage at Embry-Riddle Aeronautical University:  
<http://erau.db.erau.edu/~taam/taam.html>

Alexander Klein  
(principal inventor and author of TAAM)  
email: sak@tpg.oz.au

## **13. Summary Evaluation**

TAAM is one of the large scale, high level of detail fast-time simulations for entire Air Traffic Systems. It is currently the most fully featured ATM simulation available and with further enhancement could be incorporated into a system of models for the evaluation of concepts such as Free Flight. TAAM is undergoing further development, and The Preston Group is currently (5/14/96) working on version 3.

TAAM is a 4D flight path simulation and allows greater realism than mesh based simulations such as SIMMOD. It is possible to simulate dynamic re-routing, e.g. to avoid conflicts with other aircraft although it is not apparent whether it is sufficient to model complete Free Flight. Hazardous weather can be input as SIGMETs (severe weather advisories) and TAAM can determine which aircraft will be affected by these severe weather areas. Conflict avoidance capabilities are somewhat limited. Conflicts are detected by ghost aircraft flying the look-ahead time ahead on the prescribed flight-path. When TAAM evaluates a conflict avoidance action, it checks that the action resolves the predicted conflict between the given two aircraft, and does not lead to conflicts with other aircraft in the vicinity. If both requirements are not fulfilled, TAAM rejects the action and tries another one. TAAM cannot move more than one aircraft at a time and avoidance of one conflict can result in others that are not resolved.

### **TAAM Users**

The following organisations are major users of TAAM [TPG]:

#### **Europe:**

- DFS (German Federal Aviation Service)
- NATS / British CAA
- STCA (French Directorate General of Civil Aviation)
- Swisscontrol
- NLR (Dutch National Aerospace Laboratory)
- Aerospatiale
- Thomson-CSF

#### **USA:**

- FedEx
- Lockheed Martin
- NASA
- Boeing
- Continental Airlines
- Embry-Riddle Aeronautical University
- FAA Potomac MCF
- FAA Southern Region / Crown Communications
- New York Port Authority

#### **Asia:**

- ENRI, Japan (Electronic Navigation Research Institute)
- Airservices Australia (former CAA)
- CRC Research Institute (a subsidiary of Itochu)

## **2.2.7 HERMES: HEuristic Runway Movement Event Simulation**

(10/96 EMF)

### **1. Model Category**

HERMES is a parallel runway capacity evaluation tool. It may also be useful as a tower controller workload evaluation tool.

## **2. Summary**

HERMES is a fast-time simulation developed by the British Civil Aviation Authority/ National Air Traffic Services (CAA/NATS) to evaluate runway capacity and operations timing under current and future demand and with technological improvements. It can also be used to evaluate changes in infrastructure such as runway length modifications. While full airport operations including taxiing are simulated, HERMES puts greatest emphasis on runway operations. HERMES takes experimental recording of aircraft flight paths as input and the principal output is average delays. HERMES is effective in providing aggregate results and has been designed to account for the specific rules used at Heathrow for computing very accurate capacity estimates. HERMES is reportedly able to achieve an accuracy of 3-4 movements/24hr, as compared to 12-24 movements/24hr for SIMMOD or TAAM. HERMES also provides detailed simulation of most events occurring during take-off and landing phases.

Competing models include TAAM, SIMMOD, and The Airport Machine.

## **3. Input Requirements**

The main required input is traffic recordings. HERMES runs on 4-D traffic information obtained from experimental observations. Other inputs include aircraft mix, exit points for each aircraft, times to cross runways and resulting cross-effects on runway capacity. Aircraft are classified by speed and vortex separation categories. Traffic generation may be based on published time tables or from input parameters defining required demand profiles. Additional inputs include simulation parameters such as number of simulation runs. Currently HERMES inputs are mostly based on Heathrow/Gatwick data.

## **4. Outputs**

The main output of HERMES is a file containing average delays to all flights simulated. There is a post processor, written in C, and Excel Macros which consolidate the output files and produce delay statistics graphs. Other outputs include a log file which contains details of all actions performed by every aircraft in a given iteration. These CSV (comma separated variable) files are used for ad hoc analyses of the results. A simple text based graphics output is also available and is a useful debugging tool.

## **5. Major Assumptions**

HERMES has been custom designed for Heathrow and Gatwick and the applicability of the software to other airports is undetermined. HERMES cannot model situations involving runway crossings. The model uses experimental trajectories and does not require transcription of experimental data into a specific formats such as the link-node structure of SIMMOD. Delays are simply propagated across flight trajectories depending on occurring events. Most flight parameters can be randomized.

## **6. Computational Characteristics**

Existing code has been written in C. It is a standard PC application. No specific graphics are necessary. Eight MB of RAM are necessary.

A typical run takes about 10 minutes to complete. A typical simulation experiment will take approximately 1 to 4 weeks of staff time, depending upon how much analysis of the results is required. These timescales exclude the period required for direct observations of airfield operations, the data validation, and its entry into the simulation.

General and technical information on HERMES can be obtained by contacting David Haydon (011-44-171-832-5601).

The documentation includes file descriptions and a user manual.

## **7. Learning Effort**

Unknown.

## **8. Modularity and Flexibility**

Unknown.

## **9. Status**

HERMES is used on a regular basis for evaluation of airport improvements. It is often upgraded. The current version is HERMES II. HERMES III was scheduled to replace HERMES II in March 1996.

## **10. Extent of Model Verification**

HERMES is used on a regular basis and its output has been compared extensively with real data. The accuracy of HERMES is considered superior to SIMMOD.

## **11. Principal Applications**

Capacity change estimates for infrastructure modifications at Gatwick and Heathrow airports.

## **12. Availability**

HERMES is proprietary software owned by CAA/NATS. However, CAA/NATS has a cooperative agreement with the FAA and any contract awarded by the FAA can access HERMES.

## **13. Information for Model Evaluation and Contact Points**

Interview with David Haydon and functional description document for HERMES II.

David Haydon  
Directorate of Operational Research and Analysis  
National Air Traffic Services CAA House  
45-59 Kingsway  
London WC2B 6TE

Tel: 011 44 171 832 5601  
Fax: 011 44 171 832 6225

## **14. Summary Evaluation**

HERMES is an operational tool used to evaluate airport delays for new configurations. While the model is currently intended for Heathrow and Gatwick operations, it might be applied to other airports as well. The main input for the model is real flight data, which increases complexity, but yields very accurate aggregate results. The need for aggregate results obtained from Monte-Carlo simulations implies quite long simulation times to achieve credible results. HERMES is an appropriate tool to study cases where delays are extremely sensitive to demand variations.

### **2.2.8 NASPAC**

(ARO 9/30/96)

#### **1. Primary Model Category:**

System-wide model of air traffic flows and delays

#### **2. Summary:**

The National Airspace System Performance Capability (NASPAC) is a fast-time simulation model that may encompass large regions of airspace and a large number of airports. The simulation “flies” individual aircraft through daily itineraries (that may include landings and take-offs at a sequence of airports) and provides statistical reports on delays and flow rates observed. The model includes simplified representations of en route sectors, as well as of airports. Some graphical outputs by airport, sector or region can be provided. NASPAC was originally conceived as a macroscopic-level model that would support studies dealing with issues related to strategies for national airport investments and to policy for national and international ATM. However, much detail has been added to it over the years and it may actually be better suited today to answer questions of a more tactical nature, such as the effects on delays of alternative flow management strategies. Several variations and extensions of NASPAC have been developed in recent years by MITRE, for internal use. CENA in France has also developed a version (F-NASPAC) which is better adapted to the European ATM environment.

### **3. Input Requirements:**

The principal inputs to NASPAC, include: demand, in the form of a complete schedule of aircraft itineraries in the airspace region of interest (the demand includes both scheduled and unscheduled flights); capacities of airports and of other ATM resources, such as any modeled fixes and en route sectors; and aircraft performance data.

### **4. Outputs:**

The main outputs of NASPAC consist of estimates of delay and of flows past given points ("throughput") in the system modeled. Delay is reported in the form of "technical delay" (defined as the local delay incurred at any specific point in the system) and of "effective delay" (defined as the difference between scheduled and actual times of events, such as the arrival or departure from a gate).

### **5. Major Assumptions:**

The NASPAC simulation is essentially a deterministic one. Given a schedule of operations and a set of resource capacities, the model performs this schedule and then reports associated delays and flows. Modeling of resources is at a low level of detail, in keeping with the model's objectives. For example, an airport's capacity is a single number that represents the acceptance rate of that airport and is not concerned with gate capacity, taxiway capacity or the nuances of the runway configuration in use.

NASPAC includes a module that attempts to infer the itineraries of individual aircraft from OAG-like airline schedules. This process is, of course, an approximate one.

### **6. Computational Characteristics:**

The NASPAC simulation model is written in SIMSCRIPT II.5 and its pre-processor and a graphics and report-generating post-processor in Fortran, C and Pascal. The model runs in a workstation environment (SUN Sparcstations).

### **7. Modularity and Flexibility:**

The level of detail in NASPAC modeling can be adjusted to some extent to fit the needs of the study at hand. The pre-processor and post-processor consist of a large collection of programs that can be utilized according to need.

### **8. Status of Model:**

NASPAC was originally developed by the MITRE Corporation for the FAA during the late 1980s. After several revisions, the model was transferred to the FAA. NASPAC has also been transferred by the FAA to a small number of national and international civil aviation organizations outside the United States, such as CENA (France) and Eurocontrol, where it is used as

a research tool, as well as for support of traffic flow management operations.

The FAA has no current funding or plans for the further development of NASPAC. However, some model enhancements are taking place in connection with specific model applications. For example, CENA has implemented a number of model modifications that make NASPAC more adaptable and appropriate to the European ATM environment.

MITRE has also developed recently at least two other models which can be viewed as simplified alternatives to alternatives to NASPAC. These are Quickpac and AMC (the Aggregate Modeling Capability).

#### **9. Extent of Model Validation:**

A number of NASPAC validation efforts have taken place over the years (see, e.g., Cherniavsky, Ellen A. et al., *Validation of the National Airspace System Performance Analysis Capability Simulation Model*, MITRE Report MTR-89W00170, May 1990). Agreement with field observations has been reported to be reasonably good.

#### **10. Principal Applications:**

NASPAC has been applied in a number of instances in the United States and in Europe. For example, the model was used to assess the impact on airline delays nationwide of the (then proposed) new Denver International Airport. It was found that the proposed airport would contribute to a substantial reduction of delays on a national scale. Some applications of NASPAC have been concerned with the impacts of alternative traffic flow management (TFM) strategies. The NASPAC database currently includes the entire National Airspace System in the United States with emphasis on the 58 busiest commercial airports.

#### **11. Model Availability:**

NASPAC is not a commercially available product, but access to it can be obtained through the FAA. Occasional NASPAC-based studies in the United States are carried out at FAA Headquarters (supported by CSSI), FAA Technical Center and the MITRE Corporation. NASPAC-based studies in Europe are performed by CENA (France) and Eurocontrol, which also have copies of the model.

#### **12. Information Base for Model Evaluation:**

Presentation by Anthony Zukas (MITRE) on 12/18/95.

Interview with Steve Bradford (FAA) and William Weiss (CSSI) on 12/18/95.

Numerous informal discussions with NASPAC developers or users at MITRE, CSSI, FAA and CENA.

### **13. Summary Evaluation:**

NASPAC is the first model to be developed for the express purpose of studying the propagation of delays and congestion through a national or regional ATM system. It can be a useful tool, if utilized properly with a recognition of its strengths and limitations. For example, because the capacity of each airport in a national system can assume several different values, there is typically an enormous number of different combinations of airport capacity values that can materialize on any given day. Thus a very large number of "runs" of NASPAC, each with a different combination of airport capacity values would be needed to obtain good estimates of the mean delay values encountered in the system and of the typical range of these values (e.g., their standard deviation).

Use of the model requires considerable training and significant resources in terms of both costs and personnel. Arrangements must be made with one of the organizations that operate the model. Extensive data are also needed, but databases have by now been assembled both for the United States and for parts of Western Europe to support many types of NASPAC studies.

#### **2.2.9 TMAC**

(Last update: 3/25/96 JKK)

##### **1. Primary Model Category**

Simulation tools to analyze flow management strategies and system level evaluation of alternative operational concepts. Tools were developed to support FAA concept exploration and development.

##### **2. Summary**

TMAC is a set of capabilities and thus more than a single model. It uses aircraft flight plans, dynamics, and traffic management strategy (e.g., free-flight, limited airborne holding) to determine conflicts and delays. Uncertainties in aircraft trajectory projections are also modeled to provide realistic inputs to traffic management logic. The user is able to interact with the models for concept development. TMAC is complex, intended to solve specific problems and not meant to be a generic modeling tool. It is not available outside MITRE.

Competing models include SIMMOD, RAMS, NASPAC, TAAM, and FLOWSIM.

##### **3. Input Requirements**

Aircraft routes, flight plans, aircraft dynamics, ground delays, traffic management logic (e.g., free-flight, structured ATC, or airborne holding), airport capacity.

#### **4. Outputs**

Travel times, delays, conflicts.

#### **5. Major Assumptions**

Assumes given airport capacities but no en route sector capacities. No conflict resolution algorithms are included.

#### **6. Computational Characteristics**

Platform: 2 - HP 755 workstations (one for Sybase, one for the model)

Operating System: HP-UX 9.0.3

Memory: 384 MBytes RAM, 2 GByte Hard Drive

Software Requirements: Sybase 4.9.2, Vads (Verdix/Rational) 6.2, (Perl, C, ADA).

Documentation: No formal documents but adequate user's guides reportedly exist.

Startup Effort: High

User Interface: Adequate (GUI)

Typical Run Time: best case is 0.9 real time (i.e., slower than real time)

#### **7. Modularity and Flexibility**

TMAC is a compilation of several modules and building blocks but its complexity and focus on specific problems makes it difficult to generalize to other problems. The model is somewhat flexible in that it has been used to examine diverse traffic management strategies but is not available to users outside MITRE.

#### **8. Status**

Under continual improvement and use at MITRE. The focus has been on solving specific problems rather than the development of a more generic modeling tool.

#### **9. Extent of Model Verification**

Average 2-minute savings under free-flight determined by TMAC has been corroborated by a simulation using NASPAC and (independently) by a Delta Airlines study.

#### **10. Principal Applications**

Evaluation of traffic management strategies: limited airborne holding, free-flight vs. structured control, cooperative slot exchange, arrival flow management, airline schedule volatility, classification of weather day types for TFM.

#### **11. Availability**

Not available outside MITRE. Intended as an internal tool only.

Contact: John Pyburn, MITRE Corporation, (703)-883-5546,  
jpyburn@mitre.org

## **12. Information for Model Evaluation**

Presentation and interview with John Pyburn, MITRE, 12/18/95.

## **13. Summary Evaluation**

TMAC is a complex, multi-element simulation and analysis tool intended primarily for use in evaluating traffic management strategies. Although it is intended primarily as a strategic concept analysis tool, its level of detail is higher than that of NASPAC. The user is able to enter flight plans, aircraft type, ground delays, and traffic management strategy. Outputs include travel times, delay metrics, and conflicts. There is no conflict resolution, so the model is unable to show the impact of conflicts on traffic flow. The model is not available outside MITRE. TMAC is being actively used at MITRE in a number of TFM studies and to support the refinement and evaluation of the future NAS concept of operations.

### **2.2.10 FLOWSIM (FAA)**

(Last update: 3/6/96 JKK)

#### **1. Primary Model Category**

Model of traffic flow subject to airport capacity constraints.

#### **2. Summary**

FLOWSIM is a fast-time simulation of aircraft flow between major airports to determine delays and ripple effects induced by capacity constraints. The user enters flight plans from ETMS data, and FLOWSIM uses airport capacity models to determine delays. There is no simulation of en route operations: sectors are assumed to have unlimited capacity and aircraft are simulated by flight plan, not by dynamics. Airports have fixed capacity based on weather and configuration. Tactical and strategic studies can be conducted by using the traffic management editor to implement ground delay programs, miles-in-trail restrictions, or ground stops which then adjust the flight plan for simulation.

Competing models include AND, NASPAC, and TMAC.

#### **3. Input Requirements**

Requires ETMS data for aircraft flight plans. A database of capacity figures for 38 major airports is included with the model. These capacity figures are based on FAA EPS (Engineered Performance Standards) information.

#### **4. Outputs**

Delay metrics. The user can view delays as a function of airport and time.

#### **5. Major Assumptions**

All aircraft are assumed to follow pre-defined flight plans: there is no tactical rescheduling. En route sectors have unlimited capacity. Delays are produced based on miles-in-trail restrictions and airport capacity constraints.

#### **6. Computational Characteristics**

Code exists (written in C++) of approximately 10,000 - 20,000 lines and is very fast. The flight profile modeler and the timing routine are very robust and have been ported to other models. Platform, software, and hardware requirements have not yet been determined. Documentation quality is currently in draft for the prototype version.

Typical run time (for a complete 24 hr simulated period) is approximately 5-6 minutes.

#### **7. Modularity and Flexibility**

Extensive work would be needed to incorporate en route operations modeling and aircraft dynamics. The object structure for the flight profile model includes all characteristics of model sectors. Actual interactions between aircraft has not been developed. The code is relatively generic because some routines have been ported to other models.

#### **8. Status**

The model is intended as an experimental tool, is a "first prototype", and is not mature. The FAA has not worked on further development for the last 2 years and has no plans at this time to do so in the future. Metron, Inc. is utilizing and modestly improving the model.

#### **9. Extent of Model Verification**

Unknown.

#### **10. Principal Applications**

Strategic delay modeling given flight plans and airport capacity constraints. Specific applications are unknown.

#### **11. Availability**

Available through FAA, Metron, Inc., and ATAC. The primary constraint is that the model requires ETMS data. Contact: Steve Bradford, FAA, (202)-358-5234, sbradford@mail.hq.faa.gov

## 12. Information for Model Evaluation

Interview with Steve Bradford, FAA, 12/18/95.

## 13. Summary Evaluation

FLOWSIM at this point is an experimental tool used to estimate flight delays as a function of aircraft flight plans and airport capacity constraints. The model has no provisions for aircraft dynamics or interactions between aircraft while flying. Flight plans must be specified in advance (using ETMS data) and can be changed while the model is running by using the traffic management editor to implement ground delay programs, miles-in-trail restrictions or ground stops which then adjust the flight plan for simulation. The model allows for the rapid simulation of flight plans to determine if ripple effects may occur among airports. The simplicity of the model (as compared to TMAC, for example) allows FLOWSIM to operate rapidly (approximately 5 minute run times). The short run time suggests that a number of different flight planning strategies can be evaluated quickly, although only in an approximate manner. The code is apparently generic because some routines have been ported to other models.

### 2.2.11 ASCENT

#### 1. Primary Model Category

Air Traffic Flow Management (ATFM)

#### 2. Summary:

ASCENT (ATFM System Concept Evaluator for New Technologies) has been developed and implemented to evaluate the system-wide impact of new procedures, technologies, and improved infrastructure under existing or anticipated future approaches to ATFM. The model has been designed so that it can be used by a single analyst, requiring a minimum of overhead activity associated with defining and setting up scenarios and performing analyses. It is capable of evaluating candidate air traffic flow management approaches across a spectrum of scenario variations. Flight schedules (demand) and airport capacities (supply) have been determined to be the most significant defining factors for any given scenario. Tools have been created to allow user interaction in the creation of each of these scenario components.

The current version of ASCENT contains:

- i) models for a national network of capacitated and non-capacitated airports;
- ii) algorithms for planning ground holds and for allocating mandated delay between the ground and the air;
- iii) algorithms for (airline) tactical planning of arrivals at airports;
- iv) a system level simulation of a day's activities in the National Airspace System (NAS);
- v) database and analysis capabilities.

Supporting utility programs include:

- vi) models to simulate the evolution of airport weather and capacity;
- (vii) a tool for generating OAG-like demand schedules at airports.

Once the set up of a test case is completed, the simulation of a day in the NAS is realized, and the resulting delays and other desired evaluation metrics are computed. When weather/capacity are modeled probabilistically, their realizations may not exactly match forecasts that may have been used by algorithms that plan for ATFM activities. If at some point during the simulated day, a (weather or capacity) forecast changes, the analyst can choose to exercise an algorithm to replan ground holds or select an algorithm to tactically resequence arrivals at a given airport, both on the basis of the current state of the system and the new forecast. The analyst can also run an N-day Monte Carlo simulation based on probabilistic capacity scenarios and travel times.

ASCENT is a model whose capabilities overlap partially with those of NASPAC, TMAC and FLOWSIM.

### **3. Input Requirements:**

In setting up a simulated test case, the analyst selects a flight schedule and an airport capacity scenario as inputs. One of a set of ground-holding/arrival slot allocation algorithms is selected to create planned aircraft ground holds and slot allocations for the day. Reductions in en route times due to free flight, reductions in airport ground delay times due to the improved ground traffic management or increases in effective airport capacity due to improved arrival sequencing due to, for instance, CTAS can also be selected or specified by the analyst.

The input preparation process is assisted by the following files:

Enhanced flight schedule file- includes the information found in an OAG schedule, arrival and departure bank information at hub airports, current planned aircraft itineraries, and the cost of delays and tardiness for each aircraft.

Airport capacity profile file- includes both arrival and departure capacities for each possible capacitated airport operating configuration (an operating configuration includes the flight rules and the runways in use for arrivals and departures)

Scenario file- specifies the network of capacitated airports and the probability distribution on the airports' operating configuration for a given day.

### **4: Outputs:**

ASCENT provides the scheduled, planned and realized itinerary for each aircraft in the flight schedule; these can be output as text files for analysis in a database. In addition, numerous statistical measures are available, filtered

by the user across airlines, airports, time periods, aircraft types, etc. Many of these outputs can be displayed through an extensive menu of windows.

## **5. Major Assumptions:**

ASCENT assumes implicitly that terminal areas are the serious congestion points in the ATM system. It thus places its emphasis on modeling ATFM approaches and strategies, such as ground-holding and arrival slot allocation, designed to deal with terminal area problems. En route congestion, if any, is dealt with by simply increasing input en route travel times between airport pairs. ASCENT also utilizes simplified representations of terminal area decision support tools, such as CTAS and SMA.

## **6. Computational Characteristics:**

ASCENT requires a PowerMac or equivalent clone running MacOS System 7. The computational modules of ASCENT are written in ANSI C. For less than tens of thousands of flights, memory requirements range from 4-8MB; for tens of thousands of flights, memory requirements range from 8-12MB. The application and needed data files require less than 5 MB of hard disk space. The minimum required monitor resolution is 832 x 624, and the application can use effectively any additional monitor resolution.

Software / compiler requirements: ASCENT is a stand-alone compiled application.

Existing documentation: Minimal.

Startup effort required: Low.

User interface: Good.

Typical run time: seconds to minutes

## **7. Modularity and Flexibility:**

The code is very much object-oriented, even though it is written in C, not C++ and additional planning algorithms can be easily added. Input and output use simple text formats, providing straightforward integration with a variety of preprocessing and post-processing models.

## **8. Status of Model:**

Development of ASCENT has taken place over a five-year period beginning in 1992, with major enhancements taking place during 1996.

## **9. Extent of Model Validation:**

Validation to date has been limited to consistency testing, demonstration of capability to emulate alternative ATFM strategies and extensive sensitivity analyses.

## **10. Principal applications:**

The model is intended to serve as a tool for evaluating the system-wide impact of new procedures, technologies, and improved infrastructure under existing or anticipated future approaches to ATFM

ASCENT has been used to date as a tool for (1) demonstrating conceptually the potential impacts of alternative approaches for allocating airport arrival slots, (2) exploring the performance of alternative ground-holding strategies and (3) investigating the sensitivity of ATFM performance to changes in various system parameters, such as airport capacity, variability of aircraft spacing, flight sequencing priorities, etc.

#### **11. Model Availability:**

The executable is available to at no cost to the NASA AATT Program; it is also available for academic research. All questions on access should be directed to Dr. Milton Adams (adamsm@draper.com) at Draper Laboratory.

#### **12. Information Base for Model Evaluation:**

Robinson, J. D. (1992). *A Simulation Testbed for Flow Management Analysis in Air Traffic Control*, CSDL-T-1148, C.S. Draper Laboratory, Master's Thesis in Operations Research, MIT, Cambridge, Mass.

Hocker, Guy A. (1994). *Airport Demand and Capacity Modeling for Flow Management Analysis*, CSDL-T-1200, C.S. Draper Laboratory, Master's Thesis in Operations Research, MIT, Cambridge, Mass.

Yu, Jung (1996). *Airport Capacity and Regional Weather Modeling*, CSDL-T-1271, C.S. Draper Laboratory, Master's Thesis in Operations Research, MIT, Cambridge, Mass.

Adams, Milton, S. Kolitz and A. Odoni (November 1996). *Evolution Toward a Decentralized Air Traffic Flow Management System*, CSDL-R-2767, C.S. Draper Laboratory, Cambridge, Mass.

#### **13. Summary Evaluation:**

ASCENT has the potential for becoming a very valuable testbed for ATFM concepts and strategies because it has several unique features: easy to use and designed for operation by a single analyst; many default inputs and a highly graphical interface that greatly facilitate the definition and preparation of scenarios and the performance of analyses; pre-programming of several generic ATFM strategies for the allocation of airport arrival slots, such as "first-scheduled, first-served", "minimize delay costs", "minimize costs over a network of airports"; stochastic and deterministic airport capacity forecasts that make it possible to evaluate the performance of ATFM strategies in the presence of uncertainty; and the availability of the demand-generation tool POAGG, for easily generating OAG-like hypothetical flight schedules for a network of airports. The principal weakness at this time is that the model is new, has not yet been tested adequately or validated and is not transportable due to lack of adequate documentation.

## 3.0 CONFLICT DETECTION and RESOLUTION MODELS

### 3.0 REVIEW OF CONFLICT DETECTION AND RESOLUTION MODELS

#### 3.1.1 Definition

Traffic conflicts between aircraft flying under an advanced air traffic management concept will affect overall system benefit, cost, and safety. To examine both the potential impact of conflicts and to evaluate candidate conflict resolution strategies, it will be necessary to develop and use specialized conflict models. These models can be roughly organized into three categories, shown in Figure 1. Aircraft trajectories must be generated based on a model of assumed parameters such as aircraft type, routing logic, etc. A conflict detection model then determines which of these trajectories result in conflicts. A model for conflict resolution produces performance metrics, such as accident rate, based on a given conflict resolution approach. In more detail, we have:

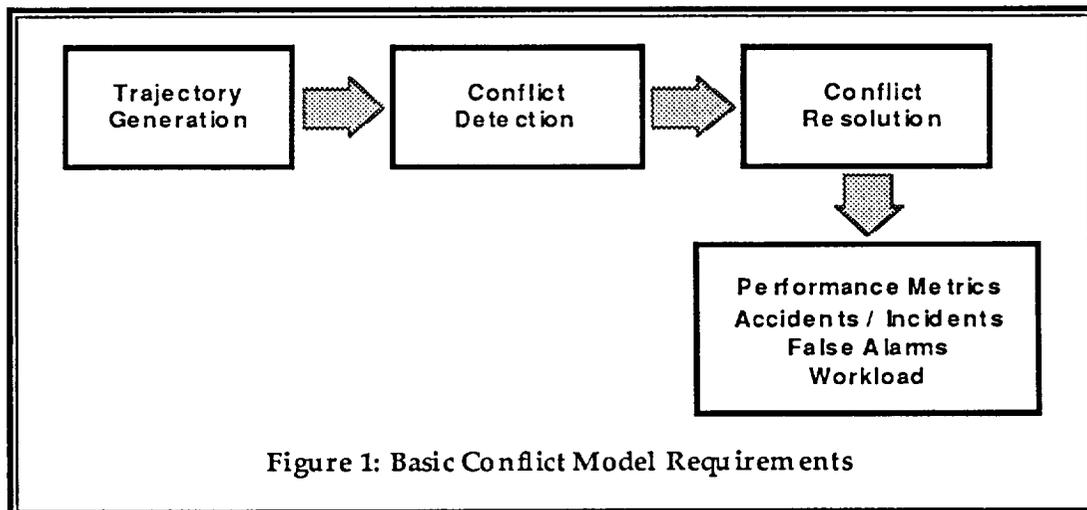


Figure 1: Basic Conflict Model Requirements

1. **Trajectory Generation:** The density (spatial or temporal) of conflicts is a predictor of the amount of intervention that will be required to maintain aircraft separation. Models of traffic flow are needed to determine the frequency and form of conflicts (e.g., the location, geometry, and number of aircraft involved in a conflict). Trajectory generation models may be developed specifically for conflict analyses or may be adapted from capacity and delay models (Section 2).

2. **Conflict Detection:** Conflict probe algorithms must be developed to alert controllers and/or pilots that a conflict exists. These probes will use sensor and datalinked information such as aircraft position and intended path to determine if intervention is required. Models are needed here to determine the effectiveness (e.g., false alarm rate) of conflict probe methods.

3. Conflict Resolution: Once a conflict is detected, a method of resolving the conflict is needed. Models are required to determine whether proposed resolution methods are effective in maintaining separation and to determine the impact of the conflict on the overall traffic flow. Additionally, depending on the ATM environment at hand, human performance considerations during conflict resolution may need to be modeled (e.g., the controller's ability to manage several aircraft at once).

Different models may, of course, cover some or all of the aspects of conflict modeling shown in Figure 1. For example, one model may only generate trajectories, while a different model may generate trajectories, estimate the number of conflicts that will occur in a certain time period, and determine the probability of an accident.

### 3.1.2 Principal Existing Models

A number of conflict models have been developed, covering a range of complexity. Many of these models are *ad hoc* and have only been exercised in specific studies although they could be generalized for more extensive analyses (for example, see [1] for several papers on ad hoc conflict detection and resolution concepts). Only major, fairly-well-generalized models are discussed below.

Models can be classified into either "node-link" or "3D" airspace. Node-Link models discretize airspace into a number of nodes and links. Aircraft move from node to node along the links and conflicts occur when more than one aircraft tries to move to a single node. Typically, these conflicts are resolved by 'delaying' one or more of the aircraft at a node. By necessity, node-link models are coarse but may provide rough initial results to identify areas where more detailed study is required. Example node-link models are ASIM, FLOWSIM, and SIMMOD. Of those, ASIM has been developed solely for facilitating the approximate estimation of the frequency of conflicts in en route airspace under various air route configurations and air traffic control densities; the model offers little else in terms of capabilities. FLOWSIM is a low-level-of-detail model concerned primarily with estimating flows and delays. SIMMOD is a general-purpose model for simulating airport and airspace operations that can also provide preliminary counts of the frequency of conflicts en route and in terminal airspace.

3D models allow aircraft to fly arbitrary three-dimensional routes. In some models, aircraft follow specified flight plans exactly; in others, a set of dynamics is used to simulate aircraft performance and flight paths may deviate from flight plans. Generally, 3D models allow for much more realistic conflict detection, and may output metrics such as minimum separation or conflict geometry. Additionally, more realistic conflict resolution is possible, generally modeled using a simplified rule-base to provide avoidance commands. Example 3D models with conflict resolution components are ARC2000, BDT, RAMS, and TAAM. ARC2000 was designed to evaluate rule-based conflict resolution strategies in a realistic environment. BDT is a very basic simulator used solely for conflict detection and resolution. Thus, ARC2000 and BDT can be characterized as special-purpose models. RAMS, by contrast, is a general-purpose tool for

airspace simulation with a conflict detection/resolution feature, among others. Similarly, TAAM is a general-purpose model for simulating airspace and airport operations. Other 3D models, which do not currently include conflict resolution, are NARSIM and TMAC.

### 3.1.3 Model Comparisons

Table 3.1 shows a comparison of the currently-available major conflict models. The Trajectory Generation column refers to the requirement that aircraft flight plans be prespecified. ASIM has the ability to incorporate either predefined flight plans or to generate flight plans based on a statistical description of flights between airport pairs. Similarly, RAMS can either take predefined flight plans or can generate lateral flight plans based on origin and destination airports (the vertical path must still be specified). For example, a company (CSSI) and the FAA have recently co-operated on developing an extensive set of predefined wind-optimal flight plans for use with RAMS. All other models require that flight plans be completely prespecified through an input file.

**Table 3.1: Conflict Model Capabilities**

<b>Model</b>	<b>Trajectory Generation</b>	<b>Trajectory Simulation</b>	<b>Conflict Resolution</b>	<b>Multi-Aircraft Conflicts</b>
ARC2000	Req'd as input	3D	Rule-Based	Pairwise
ASIM	Automatic	Node-Link	None	None
BDT	Req'd as input	3D	Algorithmic	Complex
FLOWSIM	Req'd as input	Node-Link	Delay	None
NARSIM	Req'd as input	3D	Human	Human
RAMS	Automatic	3D	Rule-Based	Pairwise
SIMMOD	Req'd as input	Node-Link	Delay	None
TAAM	Req'd as input	3D	Rule-Based	Pairwise
TMAC	Req'd as input	3D	None	None

The Trajectory Simulation column refers to whether the model uses a Node-Link airspace structure or a 3D, non-discretized airspace model. In Node-Link models, conflicts are detected only when two aircraft attempt to move to the same node. This approach is obviously unable to indicate the conflict severity or to provide details on the geometry of the aircraft involved. 3D models detect conflicts using criteria that define a conflict (e.g., minimum

miss distance or the intersection of cylinders around each aircraft). These criteria are generally specified by the user in an input file.

The Conflict Resolution column describes the method by which conflicts are resolved. "Rule-Based" resolution corresponds to the use of a set of rules by which appropriate resolution maneuvers are determined and implemented. Rule-Based resolution typically uses a single type of resolution maneuver (e.g., "jog right and then return to the flight plan"). In the case of RAMS, the Spanish Civil Aviation Authority has recently connected PUMA (a human/automation model, see next Section) with RAMS so that information can also be obtained about human workload in conflict resolution. "None" indicates that the model only counts conflicts and does not attempt to resolve them. "Algorithmic" resolution describes a model that uses more complex algorithms to resolve conflicts. "Delay" resolution indicates that the model resolves conflicts by simply delaying one aircraft at a node. "Human" indicates that conflicts are resolved in real time by a human controller; there is no automated conflict resolution.

The Multi-Aircraft Conflict column indicates the method by which the model resolves simultaneous conflicts between more than two aircraft. "Pairwise" resolution describes a model that represents these multi-aircraft conflicts as several pairwise (one-on-one) conflicts. Each conflicting aircraft pair is resolved without regard to a possible global solution. Thus, there may be multi-aircraft conflict situations that pairwise resolution is unable to resolve successfully. "Complex" resolution capabilities are currently only available in BDT and include the ability to incorporate complex conflict resolution modules using genetic algorithms or other methods. BDT has been used to resolve globally conflicts between many aircraft.

Table 3.2 outlines the major conflict-related outputs of the models listed in Table 3.1. This listing provides an indication of the level of complexity of the underlying model and its flexibility for future studies. As mentioned earlier, a number of other *ad hoc* algorithms for conflict resolution have been developed (e.g., [2]) but are not included in Tables 3.1 and 3.2 because they do not constitute formal "models". These algorithms are typically evaluated using randomly generated traffic situations and record metrics such as miss distance, number of aircraft involved in conflicts, etc.

**Table 3.2: Conflict Model Outputs**

<b>Model</b>	<b>Outputs</b>
<b>ARC2000</b>	conflict density, unsolved conflicts, trajectory deviations, time/fuel penalties
<b>ASIM</b>	conflict counts / locations
<b>BDT</b>	conflict count, miss distance, geometry, aircraft state (speed, altitude, etc.)
<b>FLOWSIM</b>	delay (position & time)
<b>NARSIM</b>	conflict detection
<b>RAMS</b>	conflict start / end times, trajectories
<b>SIMMOD</b>	delay, traffic flow (position & time)
<b>TAAM</b>	delay, conflict count & severity, unsolved conflicts
<b>TMAC</b>	delay, conflict count (position & time)

### **3.1.4 Individual Model Assessment**

The node-link models (ASIM, FLOWSIM, SIMMOD) are generally useful to determine approximate traffic density and conflict areas, but are not detailed enough for more complex studies such as determining the effectiveness of conflict resolution algorithms. Of the node-link models, SIMMOD is generally the most flexible and provides the greatest level of detail. However, none of the node-link models is particularly well-suited to flexible flight environments (e.g., Free Flight). Their use in connection with conflict frequency estimation in such environments would probably be time-consuming and not cost-effective.

Of the 3D models, only ARC2000, BDT, RAMS, and TAAM currently have the capability to detect and resolve conflicts at varying levels of complexity.

### **3.1.5 Collective Model Assessment**

The current state of conflict modeling can be summarized as follows. Simple trajectory models are typically used based on prespecified flight plans or are randomly generated based on desired traffic density. Aircraft dynamics are simple and generic (i.e., aircraft fly from waypoint to waypoint at a given speed and altitude). Conflicts are detected and counted based on simple geometrical criteria, such as miss distance or penetration of safety buffers around each aircraft. Conflict resolution is typically done through a simple rule-base and is generally not robust enough to ensure that

conflicts are resolved. BDT is currently the only model that allows complex resolution algorithms to be implemented and evaluated in a modular form. Only a few models (BDT, TMAC) include the capability to model trajectory uncertainty.

### 3.1.6 Recommended Model Toolkit

To summarize, tools are needed in the three general areas of Trajectory Generation, Conflict Detection, and Conflict Resolution. The appropriate toolkit of models would make it possible to perform studies that would (i) estimate the conflict rate, given a certain region of airspace and air traffic management concept and/or (ii) develop resolution strategies to prevent collisions once a conflict occurs.

For traditional, highly-structured flight environments, issue (i) above could be addressed by a general-purpose node-link model, such as SIMMOD, or by a special purpose one, such as ASIM. However, these node-link models are inadequate in more flexible environments, such as Free Flight, and they are just as inadequate for addressing conflict resolution strategies, i.e., issue (ii).

It is, therefore, clear that a state-of-the-art “toolkit” to support conflict generation, detection and resolution studies should consist of a combination of special purpose models, such as ARC2000 and BDT, and a general purpose model, either RAMS or TAAM.

As mentioned in Section 4 below, it is also recommended that conflict models be linked in a toolkit with human / automation models, when the controller’s ability to effect the conflict detection or resolution strategy is uncertain. Potential human / automation models include PUMA and MIDAS, both of which can be used to examine the impact of an ATM strategy on operator workload.

### 3.1.7 Recommendations for Improvement

The models discussed above generally provide the capability to examine susceptibility to conflicts and conflict resolution at a gross level. However, no single model currently provides enough flexibility and capability to perform a complete, in-depth study of conflict detection and resolution in ATM. More detailed design and evaluation of conflict resolution strategies will require more detailed tools. In particular, the following recommendations are made:

- (a) Improve Trajectory Generation Models: Estimates of the number and types of conflicts that will occur under ATM concepts are strongly tied to variables such as weather, airport capacity and demand, and flight plan generation methods. Although some tools (such as TMAC) address these issues, additional work is required to further expand and verify the assumptions and flexibility of these models. It is worth noting that some airlines currently have sophisticated trajectory generation tools that are used during daily flight planning. Efforts to transfer the expertise from airline planners to research tools would be valuable.

- (b) Expand Toolkit of Conflict Detection and Resolution Models: Current models have only crude representations of sensors, processing, and human performance. Additional development is required to expand the breadth and depth with which analysis tools can be used to evaluate conflict situations. Some studies may require rapid high level estimates of performance while others may require detailed analysis of specific situations. A toolkit should be available to allow investigators to select and use a model with the appropriate level of detail. This includes developing or enhancing tools to examine the following issues:
- (i) Level of detail of aircraft dynamic models
  - (ii) Sensor accuracy and update rate
  - (iii) Impact of intent information (e.g., knowledge that an aircraft will end its descent at a given altitude)
  - (iv) Impact of “Rules of the Road” or maneuvering restrictions (e.g., aircraft on the right has right of way)
  - (v) Differing equipment between aircraft
  - (vi) Role of pilot and ground controller in identifying and resolving conflicts
  - (vii) Human response to and interaction with conflict alert and resolution information
- (c) Develop Tools to Examine Multi-Aircraft Conflicts: There is a clear need to develop tools to examine the susceptibility of an ATM system to multi-aircraft conflicts and to evaluate candidate conflict resolution strategies during multi-aircraft conflicts. While tools such as ARC2000, BDT, RAMS, and TAAM are able to address this area to a minor extent, additional development is required to allow for more complete, flexible studies. This will require tools to:
- (i) Identify the likelihood and geometry of multi-aircraft conflicts as functions of airspace density, weather, etc. This includes developing metrics of dynamic density.
  - (ii) Develop and evaluate conflict resolution strategies. Algorithms for resolving conflicts must be developed and the methods by which resolution options are provided to a human controller need to be determined. The ability of a human controller to resolve complex conflicts may be the limiting factor in the design of the traffic management system. Thus, appropriate roles of human and automation elements must be determined. Additionally, the robustness of a given conflict resolution approach needs to be evaluated. This includes examining whether a given approach is effective in resolving conflicts and whether resolution maneuvers induce additional conflicts.
  - (iii) Determine the effect of conflicts on overall traffic flow. The frequency and types of multi-aircraft conflicts will affect the overall efficiency of traffic flow. Tools are needed in this area to determine

the potential effect that multi-aircraft conflicts will have on the larger ATM system.

- (d) Develop Guidelines for Model / Tool Evaluation: Given the growing number and diversity of analysis tools, there is an increasing need to have a set of guidelines that aid a user in understanding the capabilities and limitations of a given tool. The issues that should be considered when choosing a tool for a certain task should be clearly outlined to allow users to determine which tool is most appropriate. Additionally, when a tool is used to evaluate a proposed conflict detection or resolution method, guidelines are required to aid the investigator in assuring that all important issues are considered in the evaluation. For example, the investigator should be made aware that airspace density may affect the performance of a conflict detection system. Thus, either a range of airspace densities should be considered or the evaluation should include the caveat that the proposed system was only tested at a certain density level.
- (e) Link Conflict Models with Human / Automation Models: Establishing links between conflict detection / resolution and human / automation models would be valuable toward gaining a better understanding of constraints imposed by factors outside conflict modeling alone. For example, it could be determined that a given conflict resolution strategy is too complex or results in too high a workload for a controller to perform. Some coordinated studies have already been performed, namely using RAMS and the human workload model PUMA (see Section on Human/Automation models). Additional work is required in this area and could establish links between other models (e.g., SIMMOD and MIDAS).

## References

1. "Machine Intelligence in Air Traffic Management", AGARD-CP-538, Proceedings of the AGARD Guidance and Control Panel 56<sup>th</sup> Symposium, Berlin, Germany, May, 1993.
2. Eby, M., "A Self-Organizational Approach for Resolving Air Traffic Conflicts", MIT Lincoln Laboratory Journal, Vol. 7, No. 2, Fall, 1994.

## 3.2 REVIEWS

### 3.2.1 RAMS: Reorganized ATC Mathematical Simulator

(Last update: 10/96 EMF)

#### 1. Model Category

General purpose ATC modeling environment for enroute/ terminal airspace and controller workloads.

#### 2. Summary

RAMS is a fast-time simulation tool developed by the Eurocontrol Experimental Center (EEC) at Bretigny (France) and CACI Incorporated. RAMS is a major upgrade of EAM (Eurocontrol Airspace Model), which for the past 15 years has been Eurocontrol's principal simulation tool for evaluating proposed changes to airspace structure and sector configuration in EC member states. RAMS deals with all segments of flights starting from take-off till just before landing. However, runway interactions with airborne operations may be modeled, such as for parallel or intersecting runways.

RAMS provides a flexible airspace simulation environment where a broad variety of new concepts may be tested at the desired level of detail. Due to the flexible design of RAMS, the system is capable of carrying out planning, organizational, high-level, or in-depth studies of a wide range of ATC concepts. This design includes 4-dimensional flight profiles, conflict detection and conflict resolution mechanisms, workload models, modern user interfaces and a data preparation environment.

RAMS offers an integrated simulation study environment, with many advanced features to assist the user in the development, simulation and analysis of an ATC system.

Competing models are TAAM, ASIM, and, to a lesser degree, SIMMOD.

#### 3. Input Requirements

- Airspace description: The format used for sector definition is based on a list of corner points, 2D boundaries (a list of connected points), and the airspace definition (to add the third dimension and ATC information). RAMS has an integrated database facility which allows the extraction of data from a number of sources including the Jeppesen database of Europe, Eurocontrol or CFMU. If it is required to parse another, unsupported format, RAMS offers the possibility for users to define BNF style parsing facilities without a requirement to modify the RAMS code. FAA users have reported temporary difficulties because of the unusual airspace definition format, sometimes leading to overlapping sectors when corner points are redundant.
- Rule-based resolution system: RAMS may work with or without automatic conflict resolution. It may also run in real-time, and a human controller can then interact with the software. When running in

automatic mode, each controller in RAMS may be attributed a specific set of rules (the basic ATC conflict resolution rulebase contains over 100 rules) that RAMS will use for automatic conflict resolution. These rules may be defined sectorwise to account for local habits and working conditions.

Conflict probes can use a variety of conflict alert zone shapes. The basic shapes are rectangles, circles, ellipsoids, diamonds and users are required to select one of these only.

The separation values applied to aircraft are defined by any one of a number of sources, including the required controller separation, wake turbulence, oceanic flight metering fixes and the relative geometry of the flights in a conflict. All these features are optional and may be modified by the user.

- Flight plan description: RAMS offers the capability of simulating the entire flight plan in as much detail as desired. It can also generate flight plans automatically: Given a cruising altitude, the origin and the destination of a flight, RAMS can generate a flight plan with a climb path and a descent path based on specific aircraft performance. Aircraft performance is currently coded in lookup tables.
- Workload analysis: A virtually unlimited number of tasks may be defined for workload analysis purposes.
- Weather patterns - Special use airspace: Convective weather patterns and Special Use Airspace can be accounted for via time- varying forbidden zones.

#### **4. Outputs**

By carrying out comparative analyses between different simulated scenarios, the effects of proposed changes can be expressed in terms of:

1. Distribution of workload over centers, sectors, and individual control positions;
2. Traffic loads within each sector/center overall and per route, level band, point, classified according to cruise, climb and descent;
3. Penalties imposed upon traffic resulting from imposing ATFM measures, flight level changes, en-route/ground delays, and arrival holding.
4. Frequency distribution based on many iterations of a given scenario (Monte-Carlo simulations).

Users of RAMS have mentioned that its post-processing capabilities are rather poor. Outputs are reported to consist mainly of large, unprocessed output files (trajectories, conflict start and end times).

CSSI seems to have developed a graphical tool based on SDAT, an interactive airspace building tool, to post-process some of RAMS' outputs. The contact name at CSSI is Stephane Mondoloni.

## **5. Major Assumptions**

Unknown.

## **6. Computational Characteristics**

- **Hardware Requirements:** The system runs on HP9000 series 700 workstations. There are currently no plans to implement RAMS on any other machine.
- **Software Requirements:** RAMS comprises over 160,000 lines of ModsimII. Machines with 256 Mb of RAM or higher and a disk of 4 Gb or more are recommended for serious use of the system. MODSIM II is a fully object oriented simulation language developed by CACI Products Company that generates C code. It runs under UNIX under X-windows or its HP-Vue Window equivalent. The source code is not available to any users.
- **Execution Characteristics:** Typical speeds can range from 3 to 20 times real-time, depending on the desired simulation. Very small simulations may run up to 100 times real-time. FAA users have reported that it took 10 hours to run a 1-day, 12,000 flight simulation without conflict resolution.
- **Documentation:** According to the FAA users, the documentation to users is "adequate", and the graphical user interface is "adequate to good". A future site for RAMS information, documentation, online user support, users group and News/Discussion forum will be defined soon.

## **7. Learning Efforts**

RAMS requires relatively modest learning effort. According to the developers, two weeks are necessary to get familiar with RAMS. FAA users reported 1 month as necessary to really get comfortable. A typical initial study may require frequent contacts with Eurocontrol.

## **8. Modularity and Flexibility**

RAMS is currently a closed-architecture software system. However, the development plans for RAMS include moving towards an open architecture, where externally developed modules could bypass some of RAMS' functions (e.g. conflict resolution). AENA, the Spanish Aviation Authority, has interfaced RAMS with the surface simulation part of SIMMOD and with PUMA, the human workload simulator, with relatively modest programming effort.

## **9. Status**

RAMS official release 2.0 was carried out in November 1995. RAMS 2.1 has been released internally to Eurocontrol and will be available early May

1996. These developments include moving towards an open modular architecture.

Current RAMS users include Eurocontrol Experimental Center, FAA/OR Washington, AENA Madrid, Transport Canada. Demands for RAMS have been received from CENA (France), Irish CAA, NATS (UK), DFS Frankfurt and MIT. A first RAMS user's group meeting is planned for June 1996.

## **10. Extent of Model Verification**

RAMS has been tested by the FAA in a study to evaluate the effects of direct routing on airspace operations in New England. It has been reported as "the best available airspace simulation tool".

## **11. Principal Applications**

- ATC workload
- Free Routing investigation
- Free Flight investigations
- Airspace capacity, density

## **12. Availability**

RAMS is available from Eurocontrol. Currently, RAMS availability needs to be negotiated on a case-by-case basis.

## **13. Contacts**

Contacts in Europe:

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#### **14. Report Sources**

Interviews conducted at FAA on December 18, 1995, with Steve Bradford (FAA), Stephane Mondoloni, Willie Weiss and Bill Colligan, all of CSSI; and on January 11, 1996, at Eurocontrol with Ian Crook.

#### **15. Summary Evaluation**

RAMS is a new airspace operations simulation tool developed for Eurocontrol. While currently it has a closed-architecture, RAMS apparently offers enough freedom to investigate many aspects of future concepts such as flying direct routes. However, this simulation tool is very recent and extensive usage is necessary to fully assess its capabilities.

### **3.2.2 ARC2000: Automatic Radar Control for the years beyond 2000**

(Last update: EMF 10/96)

#### **1. Model Category**

Airspace traffic management and control model assuming advanced aircraft flight management systems.

#### **2. Summary**

ARC2000 is a tool developed at Eurocontrol Experimental Center (EEC) to assess the feasibility of automated ground-based separation assurance at a target date beyond 2015. The goal of ARC2000 is to demonstrate that automated air traffic control can maintain a conflict-free portion of the airspace for unlimited periods of time, and under high traffic densities. In particular the automatic system should be able to recover from unforeseen events and irregular operations. It is based on ideas that emerged from older projects such as ASTA (ATM Strategic and Tactical Advisor) which explored the advantages that might accrue to ATM from advanced cockpit automation.

The main assumption in ARC2000 is the availability of 4D-FMS and the ability for aircraft to fly almost exactly trajectories defined 25 minutes in advance. Controllers and sectors are virtually eliminated from the ARC2000 environment. Conflict resolution clearances are generated automatically on the ground and sent to aircraft using data-link. Consequently, ARC2000 does not provide Human Machine Interface (HMI) for controllers to manually exercise Air Traffic Control, even though the simulation is displayed on a high-resolution 29" screen used in ATC.

A significant by-product that emerged from the ARC2000 project is HIPS (Highly Interactive Problem Solver), also developed by the EEC. HIPS is an interactive conflict resolution aid which also presumes 4D-FMS

capabilities that can be used by both controllers and pilots in a decentralized conflict resolution scheme. This tool will be tested in the forthcoming European experiments PHARE Demos 1 and 3.

The ARC2000 assumes that control instructions are prepared automatically and delivered by the system to aircraft via data-link. Typically, the model assumes direct flights from zone entry to exit, although it can accommodate non-direct routings. Navigation is based on pseudo flight plans where constraints are specified in lieu of a formal flight plan (RNAV traffic). In a typical scenario most of the traffic is overflying while a significant proportion of flights depart from or enter pseudo-terminal areas with metering down to predefined levels over specified points.

The model can simulate unanticipated events or disturbances including activation/deactivation of Temporary Reserved Areas (TRAs) and flight path deviations using either the Multi-Aircraft Cockpit Simulator (MCS) or predefined data for specific aircraft. Possible degradation of aircraft capability or air to ground data exchange are not accounted for in ARC2000, however the decision -aid derivative, HIPS can account for degraded aircraft capabilities.

### **3. Input Requirements**

To run an ARC2000 simulation the following input files are needed:

1. The simulated airspace which consists of two main elements:
  - a. A description of the portion of the airspace where ARC2000 operates. This area should be large enough to provide sufficiently long flying times (greater than one hour) permitting a strategic approach to air traffic control. Interfaces with adjacent airspace should also be appropriately described. The area currently simulated is a polygon covering the northern Spain and Portugal, the western part of France and the southern part of Great Britain and Ireland.;
  - b. Traffic samples: ARC2000 uses recorded flight tracks as the basic traffic input. To model higher traffic densities flight departure times are concentrated and traffic is cloned. Two 2-hour long traffic scenarios have been generated, one with 508 aircraft and the other with 750.
2. The maneuver priorities and associated parameters.
3. The sequencing points and associated parameters. Note that sequencing can only be done at waypoints or arrival/ departure routes.
4. Deviation thresholds: The ARC2000 system monitors the aircraft positions, in order to verify that aircraft fly their predicted trajectories, and, if not, to take appropriate actions.
5. Lateral separations between aircraft: The separation standards are aircraft- and speed- dependent and have been adapted to take into account the real-life imperfections of 4D-FMS. This may result in separation standards that are higher than the ones currently in use.

6. Vertical separations.
7. The time horizon for conflict resolution.

#### **4. Outputs**

During a ARC2000 simulation each action is recorded, so it is possible to obtain statistical results about:

- the aircraft density in the airspace;
- the conflict density in the airspace;
- trajectory deviations;
- unresolved conflicts;
- extra route distances;
- other parameters

#### **5. Major Assumptions**

Each aircraft is assumed to be equipped with 4D FMS. Datalinks have infinite bandwidth and computational power is infinite. Conflict resolution is automatic.

#### **6. Computational Characteristics**

**Hardware Requirements:** The system runs on a HP 9000/755, but in principle, it could run on any machine in the 700 series, since PA-RISC 1.1 machine code was generated. The display position requires two screens equipped with PEX 5.0 servers. The supervision position requires one screen equipped with an X11 release 5 server. The screens used are each 29 inches wide. The display position uses Xlib and PEXlib software while the supervision position uses X-toolkit and Motif library software

**Software Requirements:** The ARC2000 software was written in ADA and ANSI-C and is divided into component sub-systems. There are 28 identifiable sub-systems spread over 1041 files. There are 301,093 lines of code:

- 4,465 lines of C ;
- 167,004 lines of ADA;
- 66,194 lines of comment;
- 63,430 blank lines.

**Execution Characteristics:** A typical simulation with 506 aircraft and 3 hours of traffic lasts 3 hours.

**Documentation:** The following documents are available from EEC (at Bretigny France):

1. "ARC2000 TECHNICAL REPORT" Task AS06 EEC Report: 274 (December 1994). Aside from ARC200 specific information, this document contains a detailed description of BADA (basic aircraft performance database) in use in many of the European ATC fast-time and real-time simulation facilities, such as NARSIM in the Netherlands.
2. "ARC2000 USER GUIDE' (July 1995)
3. "ARC2000 SOFTWARE SPECIFICATION 2.0" 1992
4. "ARC2000 PARAMETERS" Task AS10 Internal EEC note: 3/B2.1/1995
5. A flyer describing the main features of ARC2000
6. An overview of ARC2000 Version 3 from the operational point of view, EEC Report: 286 (1.15.1996)

### **7. Learning Effort**

The system is well documented. One beginning engineer at Eurocontrol needed 2 weeks to run a first simulation.

### **8. Modularity and Flexibility**

ARC2000 has been coded in mostly ADA, which allowed the programmers to make it very modular. For example, several subroutines of ARC2000 were subsequently integrated in HIPS with no reported problems.

### **9. Status**

ARC2000 is now frozen and HIPS is being tested in the real-time simulations, field experiments PHARE Demo 1 and 3 and in several European research Laboratories. Three people work on ARC2000 at EEC. Several more people work on HIPS (at EEC Bretigny, DRA (UK), NLR (The Netherlands)).

### **10. Extent of Model Verification**

Some of the assumptions (4D planning) within ARC2000 will be evaluated through the use of HIPS in the PHARE project (PHARE Demo 1 and PHARE Demo 3). Results are expected by 1998. ARC2000 seems not to have been used outside EEC.

### **11. Principal Applications**

Airspace Capacity Limits. Investigation of automated conflict avoidance up to 25 minutes in advance. Modelling of strategic conflict resolution for direct en-route airspace.

### **12. Availability**

ARC2000 may be available at no cost under EUROCONTROL (FAA MOC annex 5).

### 13. Contacts and information for model evaluation

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### 14. Summary Evaluation

ARC2000 is specifically targeted to the study of ground-based, automated conflict avoidance based on 4D-FMS availability. The goal is to demonstrate improvements in capacity that are possible using this method. Resolution success rate is still too low to consider operational implementation in an automated system. However, the strategic conflict resolution features of ARC2000 seem to generate very cost efficient solutions (less than 1% time and fuel penalty) under high traffic load. Those ARC2000 features could be added to RAMS to model a two-tier ATC with strategic and tactical conflict resolution.

#### 3.2.3 BDT: Banc De Test

(Last Update: NP, EF 10/96)

##### 1. Primary Model Category

Simulation tool which generates aircraft trajectories to test automated conflict resolution algorithms.

##### 2. Summary

The Banc de Test tool (BDT) was developed at Centre d'Etudes de la Navigation Aérienne (CENA) as a support tool in the AGACER project (Algorithmes Génériques Appliqués au Contrôle En Route). The main process of BDT uses aircraft flight plans and simplified dynamics to generate trajectories in a given airspace. It can be used alone to detect and count conflicts (i.e. horizontal or vertical separation violations), or used as a testbench for an independent conflict resolution module.

Competing models include RAMS, TAAM, and ASIM.

##### 3. Input Requirements

- Location of navigation beacons in the airspace;
- Basic aircraft performance data for each aircraft type;

- Flight plans containing a list of nav aids and the requested flight level.

#### **4. Outputs**

The standard outputs of the model are:

- Departure time, arrival time and delay for each flight.
- Number of airplanes in the air and their altitudes, at 5 minutes intervals.
- For each conflict: the miss distance, the aircraft involved and their positions, speeds, altitudes,...just before and just after the separation violation.

Additional code has been written to extract higher level conflict information and statistics from these standard outputs, but it is not well documented and it is not easy to use.

#### **5. Major Assumptions**

Aircraft trajectories are simplified:

Aircraft climb directly to the cruise flight level at a constant speed and rate of climb;

Airspeed and altitude are constant during the cruise segment;

Aircraft descend directly to their destination at a constant speed and rate of descent; terminal areas and airport capacity are not modeled.

Trajectory variations are modeled as randomness in ground speed and climb/descent rates.

Additional assumptions are usually made in the conflict resolution modules.

#### **6. Computational Characteristics**

The source code was written in C and was available for the evaluation. It is well structured and well documented.

1. Hardware requirements:

- platform: the evaluation was done on a Sun Sparc 5.
- operating System: Unix.
- memory: 32 Mb of RAM, 10 Mb of hard drive.

2. Software requirements: GNU C compiler.

3. Documentation: No formal user's guide is available. This is mostly a research tool. A document describing the structure and functions of the model was used for the evaluation. However this document does not contain complete information on configuration files and input/output formats.

4. User interface: Very limited. The program runs as a batch file.

5. Typical run time: A few minutes without conflict resolution. Considerably more with conflict resolution, depending on the algorithm. Typical algorithms include Genetic Algorithms.

## **7. Startup Effort**

The program is easy to run in less than a week.

## **8. Modularity and Flexibility**

The source code is modular and well organized. This is an open-architecture software system. Different conflict resolution schemes can be selected without modifying the source code. The source code was made available to MIT.

## **9. Status**

The model is continually evolving. It is currently used by French civil aviation research groups to test several automated conflict resolution schemes (including optimization by Genetic Algorithms).

## **10. Extent of Model Validation**

Unknown.

## **11. Principal Applications**

The principal application of this model is currently the evaluation of tactical conflict resolution algorithms.

## **12. Availability**

Upon request to Jean-Marc Alliot, CENA, FRANCE.

## **13. Information for Model Evaluation**

Source code, simulation runs, and discussions with Jean-Marc Alliot, Centre d'Études de la Navigation Aérienne.

## **14. Contact Points**

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## **15. Summary Evaluation**

BDT is a modular program which allows testing of new automated conflict resolution schemes at the tactical level. It is not a system-wide model, and it could not be readily used to validate Air Traffic Control concepts (e.g. Free Flight). In particular, it does not presently take into account Air Traffic Flow Management, terminal areas, airport capacities and weather. The developers plan to use RAMS to test their conflict resolution tools in a more realistic environment.

### **3.2.4 NARSIM**

(NLR ATC Research Simulator, NLR: Nationaal Lucht-en Ruimtevaartlaboratorium, National Aerospace Laboratory, Netherlands)

(Last Update 6/18/96, KK)

#### **1. Primary Model Category**

Real-time Air Traffic Control simulation with humans and real ATC systems in the loop.

#### **2. Summary**

NARSIM is NLR's in-house Air Traffic Management (ATM) and Human-Machine Interface (HMI) research simulator facility. It simulates aircraft, radar, weather and automated air traffic control. NARSIM has been used for research and development of advanced automated tools and the development integration of ground and air based systems. The advanced automated tools aid in prediction of aircraft trajectories, conflicts, and excessive deviations from the planned routes. Research in Human-Machine Interfaces is intended to aid in air traffic controllers' workload reduction.

NARSIM is also being used in international research projects such as PHARE for 4D ATM concepts which is the research part of the European Air Traffic Control Harmonisation and Integration Program (EATCHIP) conducted by Eurocontrol for the development of next decade's European Air Traffic Management System (EATMS).

#### **3. Inputs**

Complete simulation of an air traffic control system would typically require comprehensive data on the environment and agents. NARSIM premodels the basic ATC system so modifications or new concepts can be incrementally added for evaluation. Playback of real live or recorded traffic can be used for realism. Additionally computer generated traffic with pseudopilot (human blipdrivers on computer consoles) assistance may be utilized.

#### **4. Outputs**

Generally NARSIM operates in near-real time and recordings of the entire modeled and real state can be made for post analysis of events and agent or system performance.

#### **5. Major Assumptions and Limitations**

The basic ATM system modeled is that of the Netherlands and neighboring EU countries (to a limited scale). It is possible to adapt the system to other environments. The system operates in real time and principally provides a substitute for experimentation in real ATC systems. The realism of the simulation is intimately tied up with the ability to generate realistic conditions and for that purpose real live or recorded data and pseudopilots (human blipdrivers) flying computer generated traffic are used by NARSIM.

A fast time mode without humans in the loop is also available for evaluation of conflict alerting and detection tools as an example. This mode can be up to 50 times faster than real-time depending on the complexity of the simulation and computer performance.

#### **6. Computational Characteristics**

NARSIM runs principally on an HP 9000 model 887, running HP-UX with approximately 110 MIPS (45MFLOPS), 128MB memory and about 4GB disk space for simulations with moderately heavy algorithmic load. For blipdrivers and software development purposes 9 X-terminals are connected to the main NARSIM computer.

The display computers are HP 9000 models 300 and 700. The display controllers for the ATC Controller positions are two Metheus Omega 3720 controllers (being replaced by new Metheus and Barco controllers, compatible with X-Windows) connected to two 20"x20" Sony raster monitors. The main NARSIM computer links all NARSIM computers to the Internet through the NLR wide network.

#### **7. Modularity and Flexibility**

NARSIM has a modular structure, implemented using a custom CORBA-like Client/Server middleware. Modules in different languages (typically C, Ada and Fortran) can possibly run on different hosts without any knowledge of underlying distributed system. The middleware makes it possible to add and remove modules during a simulation, and also allows for connecting NARSIM to other ATC simulators or flight simulators. Several international distributed simulations have been held, connecting NARSIM to a NASA flight simulator, the NLR flight simulator and ATC simulators from Eurocontrol (France) and DLR (Germany).

#### **8. Status**

NARSIM is a relatively mature simulation system and has been used in a variety of ATM studies.

## **9. Extent of Model Verification**

NARSIM has been used extensively and as a large proportion of the simulation is essentially real, model verification is perhaps not an issue.

## **10. Principal Applications**

Evaluation of new ATM concepts and procedures in realistic partially simulated ATC environment.

## **11. Availability**

NARSIM is available at the NLR, Netherlands.

## **12. Information for Model Evaluation**

Michiels, R., et. al, NARSIM Homepage, NLR, July 21st, 1994,

NLR NARSIM Brochure

## **13. Summary Evaluation**

NARSIM is NLR's ATM research simulator and supports ATM research within NLR. This includes evaluating new operational procedures, building, testing and evaluating new controller assistance tools and prototyping man-machine interfaces. NARSIM includes the following tools:

The Trajectory Predictor(TP) tool which, based on an aircraft's flightplan, flight progress, current position and meteorological data, computes and stores the expected 4D-trajectory.

The ACOD (Area Conflict Detection) tool which supports the air traffic controller by detecting conflicts between aircraft using both planning data and actual radar data, and can therefore be considered as a medium term planning conflict detection tool.

The STCA (Short Term Conflict Alert) tool supports the executive air traffic controller by detecting future separation infringements between aircraft from data supplied by the radar data processing system, and can therefore be considered as a safety net tool for short term periods.

The FPM (Flight Position Monitor) supports the air traffic controller by monitoring flight progress, detecting deviations from the planned route and possibly suggesting corrective actions.

NARSIM is linked to the Netherlands ATC system (Schiphol) providing live radar data in ASTERIX format over a 9600 baud line. To evaluate new FMS concepts, this link is used to transmit information such as tracked radar data.

For evaluation of controller assistance tools on NARSIM there is a facility to play back recorded traffic. These recordings include radar, flightplan and meteo data as available in the current SARP system. NARSIM can also play back traffic recordings from the Maastricht Eurocontrol centre. The

collection of recorded live-traffic (approximately 30 hours) includes average and most special circumstances to appear in every-day air traffic control. Special recordings include high traffic loads due to diverted traffic from surrounding airports and bad weather conditions. To create extreme conditions several recordings can be mixed to increase the amount of traffic.

The simulation scenarios for the air system are based on a set of initial flight-plans. The scenario generator has parameters to select certain types of flight and the number of flights per minute (continuous or with randomized intervals) for each type. The output of the scenario generator is editable, and final manual adjustments are made to get things 'just right'.

NARSIM presently simulates almost all important entities involved in current air traffic control including the air traffic system, parametrized radar models, several ATM tools and display software. From a practical point of view this means that NARSIM can simulate most aspects of a real contemporary air traffic control system with some human help (such as the blipdrivers).

### **3.2.5 ASIM: Airspace SIMulation**

(Last Update: 10/96 EMF)

#### **1. Model Category**

Airspace complexity evaluation tool.

#### **2. Summary**

ASIM is a tool developed in UK at the Defence Research Agency (DRA) for the Civil Aviation Authority / National Air Traffic Services (CAA/NATS). It was designed specifically to study the impact of new route structures on the United Kingdom airspace operations. It has been used to evaluate the complexity of new airspace models (new route structures) for the period 2015+. At the current stage of its development, ASIM does not fully replicate Terminal Area operations, and operations under 10,000ft are not simulated. ASIM does not simulate traffic management functions in detail.

Competing models include TAAM, SIMMOD, RAMS.

#### **3. Input Requirements**

The ASIM input interface has been designed so as to be compatible with most standard databases (e.g. Jeppesen). The following are required as inputs:

- Specific routing node-link structure linking city pairs (similar to SIMMOD)
- Sector definitions
- Aircraft performance characteristics and preferred altitude bounds
- Flight plans

- Statistical information about the number and frequency of flights between city pairs

Traffic is generated probabilistically from the statistical information. The aircraft are simply flown from origin to destination. Flight levels are assigned randomly from a distribution based upon the aircraft type. Aircraft may climb or descend either according to specified climb schedules or follow ATC rules. While flight plans are pre-defined, actual flight times may be modeled by injecting randomness. No specific delays are modeled within ASIM.

#### **4. Outputs**

The main output of ASIM is a detailed report of close encounters between aircraft.

#### **5. Major Assumptions**

ASIM assumes fixed route structure for the airspace. There is no included weather model and no attempt is made to model controller actions. It is assumed that by introducing random variables in departure times and aircraft altitudes, a representative sample of air traffic is generated.

#### **6. Computational Characteristics**

The current implementation of ASIM is on a DEC Alpha workstation. ASIM has been programmed in MODSIM, a high-level programming language that generates C++ and C routines.

#### **7. Learning Effort**

It was reported that two people with standard training in ATC can become familiar with ASIM in less than a month. The documentation is reported to be very deficient by the developers themselves.

#### **8. Modularity and Flexibility**

According to CAA/NATS officials, ASIM has been developed for the purposes of the United Kingdom. However, the model and its underlying language are object oriented, and it should be easily adaptable to other needs.

#### **9. Status**

ASIM has been under development for 5 years. Further development appears necessary. According to the developers, ASIM should be considered a research tool. However, they also consider the basic model engine to be fully operational and properly validated. The post processing capabilities have been markedly enhanced over the last six months.

#### **10. Extent of Model Verification**

Unknown.

## **11. Principal Application**

ASIM was used within the Model Use and Fast Time Simulations (MUFTIS) project to evaluate the impact of European Advanced Traffic Flow Management on UK flights. ASIM has also been used in a number of other studies, including the European NOAA work program.

ASIM was also used to investigate new, simpler route structures in the vicinity of London. New route structures included great circles. It was found that great circles would reduce the number of conflicts, but would also increase the number of crossing points and would change the closest point of approach distribution.

## **12. Availability**

The software belongs to CAA/NATS and can be made available on a case-by-case basis.

## **13. Information for Model Evaluation**

Interview with Graham Stamp (CAA/NATS) on January 15, 1996, with Rob Whitaker (CAA/DRA) on February 13, 1996, and with Philippe Kerlirzin on January 10, 1996.

## **14. Summary Evaluation**

ASIM is an enroute simulation model tailored for the needs of the United Kingdom. Its main purpose is to evaluate the complexity of airspace under current and future route structures, including great circles, by counting the number of close encounters. ASIM is a research tool that may be made available to NASA following formal agreements.

### **3.2.6 RATSG: Robust Air Traffic Situation Generator**

(Last update: 5/8/96 JKK)

#### **1. Primary Model Category**

Tool to create scripted 4D flight paths of pseudo aircraft.

#### **2. Summary**

The Robust Air Traffic Situation Generator (RATSG) is part of the MIT Aeronautical Systems Laboratory's part-task simulation facility. RATSG allows the user to design 4D flight plans (position and time) for a number of pseudo aircraft for use in simulation studies. Waypoints can be defined relative to fixed earth coordinates or relative to a subject aircraft. The pseudo aircraft can automatically change speed, altitude, or heading in order to assure that a desired air traffic situation occurs regardless of the actions of a human pilot. Although currently used in real-time, human-in-the-loop

simulation studies, the tool could be used in fast-time traffic simulations as well.

### **3. Input Requirements**

A Graphical User Interface is used to develop scenarios and flight plans. The user can specify the number and type of aircraft, aircraft call sign, transponder status, and whether the aircraft has TCAS. Additionally, aircraft initial states (position, altitude, heading, speed) and the 4D waypoints are defined either through a text input or graphically. Voice messages can be recorded and scripted to play at predetermined times to simulate VHF communications.

### **4. Outputs**

When running, RATSG outputs pseudo aircraft state data in either real time or in fast time.

### **5. Major Assumptions**

The aircraft use simple point-mass dynamics.

### **6. Computational Characteristics**

Code exists (written in C and GL) for Silicon Graphics Indigo workstations. Typical run time in fast mode is 3 minutes for a 30 minute flight.

### **7. Modularity and Flexibility**

The code is somewhat modular and has been exported to NASA Ames for use in developing traffic encounter scenarios.

### **8. Status**

The model is still being used but is not under further development at this time.

### **9. Extent of Model Verification**

The aircraft model uses simple performance numbers as parameters (e.g., best rate of climb, gross weight, roll rate). The values of these parameters are based on published aircraft performance data but have not been otherwise validated.

### **10. Principal Applications**

Development of traffic encounter situations for human-in-the-loop simulations.

### **11. Availability**

Available through MIT. Contact: Prof. John Hansman, (617)-253-2271, rjhans@mit.edu

## 12. Information for Model Evaluation

Johnson, E. N. and R. J. Hansman, "Multi-Agent Flight Simulation with Robust Situation Generation", MIT Aeronautical Systems Laboratory Report ASL-95-2, January, 1995.

## 13. Summary Evaluation

The Robust Air Traffic Situation Generator has been implemented on a graphical workstation that communicates with the MIT-ASL Advanced Cockpit Simulator, allowing specific traffic situations to be designed and used in experiments. Traffic encounters are scripted by the experimenter using 4D waypoints (position and time). These waypoints can be located relative to fixed earth coordinates or placed relative to the subject aircraft so that potential collision events can be simulated. VHF communications can be simulated by scripting pre-recorded voice for playback during simulation runs. During a simulation, the pseudo aircraft are automatically controlled through adaptive 4D waypoints to ensure that the traffic situation unfolds as desired even if the subject performs unexpected maneuvers. In addition, because the simulation is already built around 4D waypoints, a framework is already in place to examine advanced 4D traffic control issues with multiple aircraft.

Traffic can be simulated in real time or in a fast mode. A Graphical User Interface is used to design the traffic scenarios.

### 3.2.7 TOPAZ: Traffic Organization and Perturbation AnalyZer

(Last Update: 11/1996, KK)

#### 1. Primary model category

Safety analysis of (new) operational ATM concepts.

#### 2. Summary

TOPAZ (Traffic Organization and Perturbation AnalyZer) is a tool designed to evaluate the safety/capacity for (new) operational ATM concepts for single or multiple flight phases. TOPAZ consists of a suite of analytical model based software modules, the main of which are:

- High level Petri net based simulation environment, to evaluate frequencies of non-nominal event sequences. The main numerical packages are:
  - Data base of high level Petri net modules for human, environment and systems in ATM
  - Data base of ATM related hazard types, frequencies and probability densities

- User interface for the modular development of an application dedicated high level Petri net
- User interface for the execution of Monte Carlo simulations
- Various mathematical models to evaluate fatal ATM related accidents (collision between aircraft or uncontrolled flight into terrain due to crossing a wake vortex of a preceding aircraft). There are numerical packages for the following evaluation types:
  - Numerical evaluation of probability density functions of aircraft evolution with time
  - Fitting Gaussian mixtures to empirical, Monte Carlo or numerical distributions
  - Evaluating a generalised version of the Reich collision risk model.
  - Evaluating a probabilistic risk model of crossing the wake vortex of a preceding aircraft (this package is under development at NLR's Informatics division)

The execution of a safety/capacity evaluation exercise consists of three corresponding steps:

- Assess the frequency of safety-critical non-nominal event sequences through running Monte Carlo simulations with the High level Petri net simulator.
- Evaluate the probability of fatal ATM related accidents (collisions between aircraft, or collision into terrain due to crossing a wake vortex of a preceding aircraft), through a subsequent use of the various packages.
- Through a spreadsheet, combine the results obtained into relevant ATM safety measures (fatal accident risks, economic risk, individual risk and societal risk).

### **3. Inputs required**

In order to execute an operationally truly relevant safety/capacity evaluation of a given (new) operational ATM concept, a significant amount of input material has to be collected:

- Description of the operational ATM concept to be evaluated. This might be done up to the level of human controller tasks (air and ground), air traffic procedures and technical ATM/CNS systems. Starting from a less

detailed description is possible, however, the safety evaluation results will be less precise (when comparing conceptual designs this even may be an advantage).

- Statistical characterisation of the air traffic scenarios to be evaluated; i.e. traffic flow(s), aircraft types, etc.
- Identification of all relevant hazards, including a qualitative evaluation of their effects. This is accomplished through executing a preliminary hazard analysis which pays proper attention to all possible sources of non-nominal events (human, procedures and technical systems).
- Develop a high level Petri net model for the operational concept to be evaluated. This high level Petri net model should be of sufficient detail to represent all event sequences which may play a critical influence on the safety/capacity assessment.
- Identification of parameters or parameter ranges for all elements which may have a critical influence on the safety/capacity assessment. This is accomplished through collecting statistical data from appropriate data bases, and through assessing the allowable ranges of the design parameters.

#### **4. Outputs**

With the help of TOPAZ it is in principle possible to evaluate the safety characteristics of an arbitrary (new) operational ATM concept considered, due to safety critical non-nominal event sequences. The outputs provided consist of frequencies for the occurrence of non-nominal event sequences, conditional probabilities of collision (or hull loss) for different types of non-nominal event sequences. The practical interpretation of these figures is supported by a tree-wise representation, with at the top an overall risk measure. If desired, TOPAZ executes safety assessments as a function of scenario parameters, e.g. traffic flow.

#### **5. Major Assumptions and Limitations**

In order to keep things computationally manageable, the level of detail which can be handled for each ATM entity is limited. As such the nominal models used within TOPAZ are less detailed than those commonly used in fast-time air traffic simulation environments (e.g. TAAM). In return, however, TOPAZ enables a probabilistic incorporation of rare non-nominal event sequences within the analysis. Another limitation is that for every instantiation of an operational ATM concept, TOPAZ will often need an appropriate adaptation of already available high level Petri net modules. For such adaptation a high level of expertise is required from multiple domains (stochastic modelling, human factors, air traffic expertise).

#### **6. Computational Characteristics**

Platform: PC

## **7. Modularity and Flexibility**

TOPAZ is a highly modular and flexible system.

## **8. Status**

TOPAZ is under continual development for application to advanced operational ATM concepts.

Halfway 1996, TOPAZ has reached a certain level of maturity for the safety assessment of Dependent Converging Instrument Approaches (DCIA) with help of MITRE's Converging Runway Display Aid (CRDA).

## **9. Extent of Model Verification**

The software implementations of the high level Petri net and the Generalised Reich collision risk models have been verified for correctness, with extensive use of the mathematical basis of those models. Beyond this level, the results obtained have been discussed with experts. In the latter case it rather would be better to speak about corroboration.

## **10. Principal Applications**

- DCIA/CRDA safety assessment for Schiphol airport (Amsterdam)
- Analysis of advanced ATM concepts in Europe
- Analysis of Free Flight concept

## **11. Availability**

TOPAZ is available through the

NLR, National Aerospace Laboratory  
PO Box 90502, 1006 BM  
Amsterdam Netherlands

Contact:

Henk Blom  
+31 20 511 3544  
blom@nlr.nl

## **12. Information for Model Evaluation**

Information from developers.

- I. G.J. Bakker and H.A.P. Blom, Air traffic collision risk modelling, Proc. 32nd IEEE Conf. on Decision and Control, December 1993, pp. 1464-1469 (NLR report TP 93292 U).

- II. G.J. Bakker, Traffic Organization & Perturbation AnalyZer (TOPAZ), NLR report TR 94040 L, 1994.
- III. Blom and G.J. Bakker, A macroscopic assessment of the target safety gain for different en-route airspace structures within SUATMS, NLR report CR 93364 L, 1993.
- IV. Everdij, M.B. Klompstra, H.A.P. Blom and O.N. Fota, Final report on Safety model, Part I: Evaluation of hazard analysis techniques for application to en- route ATM, NLR report TR 96196 L, December 1995.
- V. Everdij, M.B. Klompstra and H.A.P. Blom, Final report on Safety model, Part II: Development of mathematical techniques for ATM safety analysis, NLR report TR 96197 L, March 1996.
- VI. Everdij, G.J. Bakker and H.A.P. Blom, Application of Collision Risk Tree Analysis to DCIA/CRDA through support from TOPAZ, NLR contract report, 1996.
- VII. Everdij, H.A.P. Blom and M.B. Klompstra, Extending Petri nets for Air Traffic Management safety purposes, Paper to be published in 1997.

### 13. Summary Evaluation

TOPAZ enables the evaluation of safety for a given (new) operational ATM concept during a particular or during various flight phases. In order to execute such evaluation, TOPAZ consists of a suite of analytical model based software modules, the main of which are a high level Petri net based simulation environment and mathematical packages to evaluate ATM related incidents. The nominal events modelled within TOPAZ may be less detailed than those commonly used in fast-time air traffic simulation environments (e.g. TAAM). In return, however, TOPAZ enables a probabilistic incorporation of rare non-nominal event sequences.

TOPAZ is an analysis tool for the numerical evaluation of collision risk using the generalized Reich collision risk model as described in the paper (Bakker & Blom, 1993).

TOPAZ allows safety and capacity assessment for evaluation of new route structures in combination with new ATM concepts. Collisions of all types are considered: head-flank, head-head, head-tail, flank-flank and top-bottom.

TOPAZ simulates the probability density functions along the 3D route structure rather than the individual aircraft trajectories and evaluates the collision risk between aircraft as a function of traffic flow. Maximum capacity is determined as that where the risk coincides with a preselected target value.

## 4.0 HUMAN / AUTOMATION MODELS

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### 4.1 REVIEW OF HUMAN / AUTOMATION MODELS

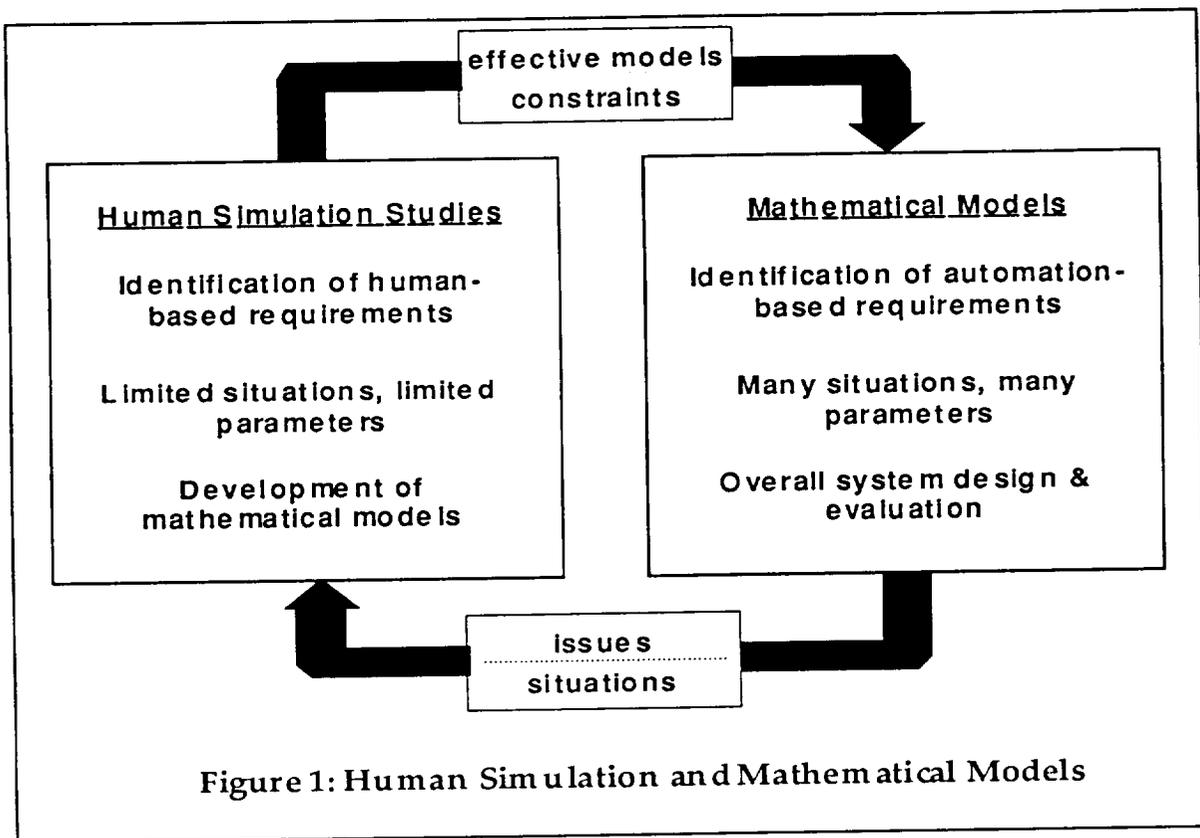
#### 4.1.1 Definition

Human/automation models are used to investigate issues that place requirements on or result from the interaction between humans and automation. Additionally, human performance is often a critical factor in the safety of a system and must be considered during risk analysis. The human can be a pilot or a ground controller and the automation may affect an aircraft, air traffic control station, or the entire air traffic system. Because humans are extremely complex components of the larger system, these models typically attempt to capture the most essential aspects of human performance, but obviously cannot fully describe it.

#### 4.1.2 Principal Existing Models

Human/automation modeling capabilities range from human-in-the-loop, real-time simulation environments to complex computer-based, fast-time mathematical models and simulations of human behavior (Figure 1). Human-in-the-loop simulation studies are typically used to determine human-centered requirements (e.g., the minimum information set needed by a pilot to determine an appropriate course of action) as well as human-induced constraints (e.g., the number of aircraft that can be handled simultaneously by the control team of an enroute sector). Typically, these studies can be quite detailed, but also require a large investment of time, resources, and equipment; thus only a limited set of conditions can generally be examined. Additionally, human-in-the-loop simulation studies are often limited to examining only incremental system evolution: revolutionary concepts can be difficult to incorporate when using hardware designed for (and humans trained for) existing systems and their immediate extensions.

Results from human-in-the-loop simulation studies can be used to develop mathematical models that can, in turn, be used to examine a wider range of conditions. These models incorporate a representation of the salient human parameters (e.g., reaction time) that may impact the overall system under study. System-level requirements and constraints (e.g., required sensor accuracy) can then be determined in fast-time, using numerical simulation, over a wide range of conditions. Results and issues raised from the fast-time simulations are then used to better focus future human-in-the-loop studies. This, in turn, leads to an improved understanding of issues related to humans and automation in ATM and thus, eventually, to better mathematical models. In this way, human-in-the-loop simulations and mathematical model studies complement one another.



Mathematical models of humans can be classified as macroscopic or microscopic. Macroscopic models can be used in stand-alone form to provide approximate estimates of human performance for a single condition or they can be incorporated into fast-time simulations for representing overall human performance. Generally, macroscopic models are useful for statistical studies intended to explore the performance of a system that has many human operators. Macroscopic models are less useful for predicting the performance of specific individuals. Example macroscopic models include McRuer's crossover model for manual control tasks or utility theory models for decision making tasks [1]. Numerous ad hoc macroscopic models exist, such as simple models of expected pilot reaction time (latency) to a warning signal. Additionally, techniques, such as neural networks or fuzzy logic, can be used to provide a relatively simple representation of a complex decision making process.

Microscopic models are detailed representations of humans typically used in discrete-time simulations of a human operating within a larger system, such as an aircraft or an air traffic management system. Typically, the human's actions are modeled using a complex set of decision rules or algorithms. These models attempt to explicitly anticipate a human's actions based on his or her sensory inputs, rather than simply capturing approximately the overall consequences of these actions, as is done in a macroscopic model. Two examples are DORATASK and PUMA, which estimate the overall workload on an operator by using detailed representations of the workload required to perform specific tasks. A third, very broad, microscopic model

is The Man-Machine Integration, Design, and Analysis System (MIDAS). These models are described below.

### 4.1.3 Model Comparisons

Table 4.1 identifies five basic applications of human / automation modeling and the three approaches outlined above: human-in-the-loop models and macroscopic and microscopic mathematical models. The five categories along the top of the table can be loosely described as follows. Situational Awareness involves the determination of how the human's mental model of a situation matches with the true situation. Flight Planning seeks to understand strategic planning and multi-attribute optimization performed by humans in connection with a flight. Decision Making refers to more tactical, short-term, flight-related, human decision processes. Task Allocation and Workload is concerned with how the human operator prioritizes tasks, how tasks affect workload, and how workload affects task performance. Finally, Human-Automation Interaction refers to modeling the processes by which a human operator obtains information from and directs tasks using automation.

**Table 4.1: Human / Automation Tools and Models**

Approach	Application				
	Situational Awareness	Flight Planning	Decision Making	Task Allocation & Workload	Human-Automation Interaction
Human in the Loop	Interview / Observation Part-Task Simulation Full Mission Simulation Shadow Study Full System Test				
Macroscopic Models	Ad Hoc Models	Decision Rules Utility Theory Fuzzy Logic		Time Sharing / Capacity Models Resource Theory	Ad Hoc Models
Microscopic Models	MIDAS			DORATASK PUMA	

Human-in-the-loop studies are real-time and thus outside the scope of this review. They are mentioned here for completeness. They range from focused interviews and observation, to part-task simulation, to full mission simulation, to system tests using actual equipment in the field. Shadow studies are also useful, in which a new approach is evaluated using actual

data feeds in parallel with actual operations. Studies at the interview level are generally less expensive, have wider scope, but are less detailed than simulation or full system tests. Thus, there is a natural tradeoff between level of detail and scope / cost.

Many *ad hoc* mathematical models exist, but only a few have been developed to stand alone as generic tools for use in more than one study. Macroscopic models are often analytical methodologies and equations that describe human / automation interaction in general form. As such, these models can provide a rough estimate of human capability and performance but are often too generic to provide estimates for specific conditions.

Microscopic models are intended to be high-fidelity representations of humans. These models may be specific to a single type of task or situation or may attempt to cover a range of conditions. A model such as MIDAS is designed to cover a range of tasks including situational awareness, planning, decision making, workload analysis, and interaction with automation. DORATASK and PUMA, on the other hand, focus only on workload. DORATASK models workload by summing the times spent on elemental activities such as communicating with aircraft, writing on flight strips, etc. PUMA uses a specific listing of tasks along with Multiple Resource Theory to estimate workload. Thus, PUMA contains a macroscopic model (based on Resource Theory) but is listed here as microscopic due to the additional requirement that the operator's tasks must be described in detail and that the computations occur in discrete time increments.

#### 4.1.4 Individual Model Assessment

MIDAS is a complex numerical simulation model that has already been used in several studies. MIDAS includes a set of modules that represent human perception, cognitive behavior, and responses to allow analysis of areas such as information management, cognition, and workload. MIDAS also allows for the inclusion of probabilistic events and errors and is able to model interruption and resumption of tasks in single and multiple operator interaction.

Because MIDAS is so complex, it is computationally intensive and needs to be adapted to each new application through the definition of input / output parameters and a detailed knowledge base. Additionally, it is sometimes unclear how accurate MIDAS is in representing human performance. Several human/automation studies have already been performed using MIDAS, and their results were subsequently verified through human-in-the-loop simulations. Still, the flexibility, adaptability, and validity of complex models like MIDAS needs to be more fully determined.

For workload-specific studies, the only models identified for evaluation (other than MIDAS) were DORATASK and PUMA. Each model requires that operator tasks are defined *a priori*, and, based on those tasks, an estimate of workload is constructed. Example tasks include looking at a radar display, pressing a button, and communicating with aircraft. DORATASK estimates the overall controller workload for an air traffic sector and has been validated in several sectors in the UK. PUMA provides

a more detailed output of workload vs. time and is therefore more suited to studies investigating specific operating procedures. DORATASK is recommended for large-scale workload studies of entire sectors, while PUMA is recommended for smaller-scale, detailed studies of specific operating environments.

#### 4.1.5 Recommendations

The high costs and time associated with human-in-the-loop simulations drive the need for mathematical models of humans that can be applied in fast-time studies to rapidly examine (and evaluate in a preliminary way) new ATM concepts. There are several approaches that can be taken to model humans. One approach (microscopic) is to model the entire process from sensory input and mental processing to actuation. The other (macroscopic) is to represent the human more broadly by describing the transfer function between input and output without modeling the details of how the process actually works. As is the case for PUMA, it is also possible to combine macroscopic and microscopic elements into a single hybrid model.

Each approach has its benefits and limitations. Specifically, it is important to consider the validity and flexibility of a model vis-à-vis different applications. A microscopic model like MIDAS provides a very detailed description of how the human operates and can provide insight into where bottlenecks are and how performance could be improved. However, whether the additional level of detail in MIDAS is really needed and whether a given version of MIDAS can be extended to cover a novel situation still needs to be determined.

In general, the area of human/automation modeling is clearly one that deserves urgent attention and investment of resources. Several areas in particular stand out in need of development:

- (a) Macroscopic Models: Because of the need to broadly evaluate how humans will react and adapt to advanced and complex air traffic management concepts, it is believed here that efforts in macroscopic modeling of human performance under a range of conditions may be particularly cost effective and pressing at this time. A set of fairly simple models that capture the essence of human performance characteristics is probably sufficient for concept evaluation at this stage.
- (b) Model Development and Validation Methodologies: Current mathematical models of humans are ad hoc, limited, and immature. New, widely-applicable models will be needed in the near future. It is important to note, though, that much of the required work is of a fundamental nature: in addition to the need to develop models themselves, there is also a need to better develop the “science” and methodologies by which these models will be generated and validated. As an example, there is a need to map out the specific space of applications to which MIDAS can and cannot be applied. The process by which human-in-the-loop experiments can be used to develop and validate simple, broad mathematical models is also immature and will require additional research.
- (c) Safety Modeling: A critical area for more research is related to the effects of humans and automation on overall system safety. Especially important are

tools that model low-probability events (e.g., human blunder or misinterpretation of automation) which have a large impact on safety. Exact probabilistic models are not possible, although the key problem areas and their potential ramifications can be determined. Currently, there is no structured way that such modeling is performed, and the need to do so will grow as systems become more complex.

- (d) Linking Human/Automation Models to Other Areas: Because of the potentially strong constraints that human performance can place on the design of an ATM concept, it will be imperative that human/automation models be used at some point during the design and evaluation process. Currently, however, there are few links between models such as SIMMOD and human performance models (one exception is a link between PUMA and RAMS). Additional effort is needed to produce links between airspace models (e.g., SIMMOD) and human models (e.g., MIDAS). It is recommended that these links be created in a modular fashion (e.g., passing data between RAMS and PUMA) rather than developing single complex models that attempt to model traffic flow, conflict detection and resolution, and human / automation issues.

## References

- [1] Wickens, C. D., Engineering Psychology and Human Performance, Harper-Collins, 1992.

## 4.2 REVIEWS

### 4.2.1 SDAT: Sector Design Analysis Tool (FAA)

(7/22/96, KK)

#### 1. Primary Model Category

Terminal and enroute sector design and controller workload analysis

#### 2. Summary

SDAT has been developed by the FAA as an analytic tool for assistance in evaluation of changes in airspace design and traffic routing. SDAT takes the existing airspace and traffic data, reduces it to more manageable form, and allows the user to select, modify and add to the data interactively for display. Various customizable analyses based on conflict probabilities can then be run to provide metrics such as conflicts, traffic loading, impacts on users and sector controller task loads.

#### 3. Input Requirements

SDAT can import standard airspace data:

- Airspace data: sector boundaries, NAVAIDSs, fixes, routes etc. from ACES & Adaptation data.
- Traffic data: from Automated Radar Tracking System (ARTS), System Analysis Recordings (SAR), Continuous Data Record (CDR) or the Enhanced Traffic Management System (ETMS).
- Supplemental data: e.g. Special Use Airspace (SUA)

These are combined for display and analysis and raw traffic data reduced to show changes only in direction, climb rate, speed or controlling sector. Interactive or text mode modifications of airspace and traffic data can be performed for the problem at hand.

#### 4. Outputs

The principal outputs are:

- 3D conflict analysis:
- potential hotspots for crossing or merging paths where need for increased separation exists
- locations, frequencies and expected per sector and per flight conflict potential
- on screen and text output
- Traffic volumes in sectors: counts, durations and throughputs determined from sector boundary crossings
- Impacts on users from changes:

- flight time: based on average speed on each route segment
- Total flight distance
- sectors traversed
- DOC based on average hourly cost for aircraft
- Sector controller task loads: actions, messages, time required etc. calculated from exchanges of HOST data.

## **5. Major Assumptions and Limitations**

Unknown. Dependence on recorded traffic data.

## **6. Computational Characteristics**

SDAT has been written in C and operates in UNIX and X-Windows with the Motif window manager. The platform currently supported is HP workstations with HP-UX with future support for SUN systems.

There are three versions:

1. SDAT: Airspace and traffic at a single ARTCC
2. Regional SDAT: Airspace and traffic at upto 8 contiguous ARTCCs
3. Terminal SDAT: for terminal facilities

## **7. Modularity and Flexibility**

Unknown. Interface to SIMMOD planned.

## **8. Status**

Under development and operational test.

## **9. Extent of Model Verification**

The core conflict analysis sector ranking has been found comparable to ranking by other methods (conflict alerts, operational errors and controller surveys).

## **10. Principal Applications**

Sector redesign evaluation

## **11. Availability**

The software is available from FAA ORLAB. For information contact:

SDAT Program Manager  
c/o ASD-400  
Federal Aviation Administration

800 Independence Avenue SW  
Washington DC 20591  
(202)-358-5223

## 12. Information for Model Evaluation

Kenneth Geisinger (FAA)  
e-mail: kgeisinger@mail.hq.faa.gov

SDAT Users' Guide

SDAT Task Load Model User Manual

SDAT Brochure

## 13. Summary Evaluation

SDAT (Sector Design Analysis Tool) is an analytic tool for evaluation of changes in airspace design and traffic routing. SDAT uses the existing airspace and traffic data. It then reduces the traffic data to remove extraneous detail and allows the user to select, modify and add to the data interactively for display. Various analyses can then be run to provide metrics such as conflicts, traffic loading, impacts on users and sector controller task loads.

SDAT has been designed to be user friendly with a GUI interface and on-line help facilities. Graphical displays of data and analyses results showing user selected information are available:

- Sector geometries
- Traffic paths
- Conflict hotspots
- Flight timelines
- Sector traffic and task loadings

SDAT takes the actual observed tracks, simplifies them into linear segments and determines the crossing points. Conflict probabilities for these points are then determined by assuming the aircraft to be randomly distributed in time along these tracks. The analysis is performed mathematically in a single run as compared to simulations which use multiple time-stepping runs with randomization (Monte-Carlo) to get statistical measures.

### 4.2.2 DORATASK

(Last update: 08/08/96 KK)

#### 1. Primary Model Category

Sectorwise controller workload modelling

#### 2. Summary

DORATASK is a fast-time simulation developed by the CAA(UK) for evaluating sector capacity based on controller workload limits by

systematically summing up the time the controller might spend on observable and non-observable tasks for each category of traffic in a sector. It follows from the simulation model RECEP(US) and complements CAA's CATSIM model. It allows prediction of capacity changes resulting from changes in manning levels, route structures or relative traffic loadings, ATC procedures or equipment, and airspace re-sectorization. DORATASK defines the capacity of a sector as that which creates a level of workload equal to a specified level (e.g 48 occupied minutes per hour).

### **3. Input Requirements**

Sector geometry, routes, task timings (determined from video, microphone recordings or otherwise) etc...

### **4. Outputs**

Workload limited sector traffic limits.

### **5. Major Assumptions**

Availability of typical activity times. Designed for UK sectors and procedures etc..

### **6. Computational Characteristics**

Machine and system: Not known

Learning effort: High; training needed, in addition to familiarity with sectors, traffic and procedures.

No documentation is available.

### **7. Modularity and Flexibility**

Apparently standalone. Extension to dual controller sectors being developed as well as other algorithmic enhancements.

### **8. Status**

The model is currently being used by CAA for UK sectors. Since 1992 it has been used for capacity assesment of the London Area Traffic Control Centre (LATCC), Scottish area (ScATCC) and the UK's CCF.

### **9. Extent of Model Verification**

The model has been calibrated against many sectors in the UK with other capacity methods or empirical data. Caution is urged by the CAA in applying the model to sectors which it hasn't been calibrated for, as unexpected interactions may arise.

### **10. Principal Applications**

Sector capacity assesment specific to the UK.

## **11. Availability**

Available from the CAA with permission.

## **12. Information for Model Evaluation**

Arnab Majumdar  
Eurocontrol  
e-mail: arnab.majumdar@eurocontrol.fr

## **13. Summary Evaluation**

The DORATASK method has been developed by the UK CAA's Directorate of Operational Research and Analysis (DORA). The DORATASK method models workload by summing the times spent on elemental activities such as communicating with aircraft, writing on flight strips, communicating with neighbouring sectors, etc. The capacity of a sector is then the maximum number of aircraft which would cause the controller to be saturated for no more than a specified percentage of time. This works well for predicting sector capacity in today's system where many fine details of the system are known, but there are difficulties in applying it to future systems where such details are not yet known.

### **4.2.3 MIDAS: Man-Machine Integration, Design, and Analysis System**

(Last update: 3/25/96 JKK, KK)

#### **1. Primary Model Category**

Human factors and performance analysis of complex man-machine systems. Also includes extensive CAD capabilities for equipment design and avionics layout.

#### **2. Summary**

MIDAS is a set of modules that allow simulation of humans interacting with crew station equipment, vehicle dynamics, and a dynamically generated environment. Computational models of the operator, the crew station, and the environment of the vehicle are implemented with emphasis on operator performance under mission conditions. Detailed models of human perception, cognitive behavior (including heuristic knowledge bases and decisions), and responses allow analysis of critical areas of human performance such as information management, cognition, and workload. MIDAS also allows for the inclusion of probabilistic events and errors and is able to model interruption and resumption of tasks in single and multiple operator interaction. Several adaptations of MIDAS to the commercial aviation domain have been developed, including Taxi-MIDAS and Air-MIDAS.

### **3. Input Requirements**

Required inputs depend on the modules being used. In Air-MIDAS, inputs include:

- The mission and activities to be performed, including probability distributions describing when events occur.
- Operator characteristics, including knowledge bases and decision rules.
- Additional modules can be used, incorporating inputs such as anthropometric models, vehicle dynamics, and perception / attention models.

### **4. Outputs**

- Human factors analysis such as reachability and visibility
- Visualization of simulated mission scenario (time lines of events and activities)
- Measurements of mission and operator performance
- Information requirements analysis

### **5. Major Assumptions**

The human operates according to a set of definable decision rules.

### **6. Computational Characteristics**

- Platform: Silicon Graphics Onyx with Reality Engine-2 Graphics. MIDAS can also run on lower-end SGI workstations.
- Operating System: IRIX 5.2
- Memory:
- Software Requirements: Allegro Common LISP 4.2 with CLIM 2.0 from Franz. Inc. is required for the LISP components of the code. Other components are written in C and C++.
- Documentation: Description of the various modules and their inputs and outputs. A users manual is currently under revision.
- Startup Effort: High User Interface: Adequate. GUI-based, under continuing development

### **7. Modularity and Flexibility**

MIDAS is modular, with the user able to specify which modules are active. A list of components is attached.

### **8. Status**

Under continual development, not mature.

## 9. Extent of Model Verification

Data generated by MIDAS for a problem investigating descent clearance timing have been compared to full-mission LOFT-type data and found to be consistent.

## 10. Principal Applications

Taxi-MIDAS preflight checklist study

Air-MIDAS has been used to examine the effect of the time at which a descent clearance is given (relative to the programmed top-of-descent point) on the choice of descent mode (i.e., autopilot vs. flight management system reprogram). Also examined were the effect of voice communications relative to datalink and pilot ability to successfully initiate the descent before reaching the top-of-descent point.

Westinghouse nuclear power plant comparison of paper and electronic procedure aiding

Richmond, CA emergency 911 dispatch workstation layout

High Speed Civil Transport flight deck analysis

Air Warrior air crew protective suit design

Short Haul Civil Tilt Rotor cockpit and crew procedure design.

Helmet Mounted Display analysis

Liquid Crystal Display analysis

## 11. Availability

MIDAS is available through the NASA Ames Research Center and Sterling Software. Contact: Kevin Corker, (415)-604-0055, kevin\_corker@qmgate.arc.nasa.gov

## 12. Information for Model Evaluation

"Army-NASA Aircrew/Aircraft Integration Program: Phase VI A3I Man-Machine Integration Design and Analysis System (MIDAS) Detail Design Document."

Corker, K. and G. Pisanich, "A Multiple Agent Model of Human Performance in Automated Air Traffic Control and Flight Management Operations", Proceedings of the Fifth International Conference on Human-Machine Interaction and Artificial Intelligence in Aerospace, Toulouse, France, Sept. 27-29, 1995.

Corker, K. and G. Pisanich, "Analysis and Modeling of Flight Crew Performance in Automated Air Traffic Management Systems",

Proceedings of the Sixth IFAC/IFIP/IFORS/IEA Symposium on Analysis, Design, and Evaluation of Man-Machine Systems, Cambridge, MA, June 27-29, 1995.

A summary of MIDAS is also provided at its website.:

[http://ccf.arc.nasa.gov:80./af/aff/midas/MIDAS\\_home\\_page.html](http://ccf.arc.nasa.gov:80./af/aff/midas/MIDAS_home_page.html)

### **13. Summary Evaluation**

MIDAS is a collection of experimental computational tools for evaluating human factors and performance analysis of complex man machine systems. The model is made up of several modules that can be independently turned on or off according to the problem under consideration. Modules include models of human vision, attention, perception, internal representation of the world, decision rules, and responses. Aircraft dynamics, guidance, environment, and terrain data may also be included.

For a given problem, the user provides a model of the environment, events that are to occur, and probability distributions. Also provided are the decision rules the human uses in acting on the information that is observed. MIDAS then runs through a simulation in 100 msec time increments, simulating the occurrence of events and the actions taken by the human in response. A timeline showing when events and actions occurred is then provided as output. By running many simulations in a Monte Carlo fashion, statistical results can be obtained.

MIDAS has been used to examine the effect of the time at which a descent clearance is given (relative to the programmed top-of-descent point) on the choice of descent mode (i.e., autopilot vs. flight management system reprogram). Also examined were the effect of voice communications relative to datalink and pilot ability to successfully initiate the descent before reaching the top-of-descent point.

Some of the limitations mentioned in the design document are:

- Difficult to Use
- Extremely Data Intensive
- Unintegrated user interfaces
- Lack of validation/verification of models
- Extremely slow speed of simulation
- Many undeveloped components

MIDAS is a very complex model intended to simulate complex situations and human cognitive processes. It has been used in some limited studies using a subset of the available modules. Verification of results will be a significant challenge in the future.

### **14. MIDAS Modules**

1. Cockpit Design Editor (CDE)
2. Anthropometric Model (Jack')
3. Vision Modeling Tools

4. Agents(including Communication Methods and Biographers
5. Pseudo Agents
6. Activity Representation
7. Simulation Executive
8. Mission and Standard Operating Procedures (MSOP)
9. Equipment Model
10. Flight Dynamics
11. Guidance
12. Terrain
13. Environment and other Objects
14. Vision
15. Perception/Attention
16. Updatable World Representation (UWR)
17. Daemons
18. Decision-by-rules
19. Decision-by-algorithm
20. Symbolic Operator Model (SOM)
21. Scheduler
22. Task Loading Model (TLM)
23. Motor
24. Anthropometric Model for Simulation (Jack Agent)
25. Visual Editor and Simulation Tool (VEST)
26. User Interface
27. Equipment Editor
28. Activity Editor
29. Statistics

#### **4.2.4 PUMA (DRA)**

(08/07/96 KK, to be updated)

##### **1. Primary Model Category**

Human Factors: workload modeling.

##### **2. Summary**

PUMA is a method and toolset for the modelling, in fine detail, of human workload. It was developed for NATS to help them in their work on future upgrades to NERC (New En Route Centre, the en route air traffic control centre for the London FIR). PUMA allows expressing controller tasks, defining a scenario of aircraft movements, and calculating the workload that results as the scenario plays through and the tasks are executed (and then altering tasks, repeating the calculation, and seeing the changes in workload). It uses the Wickens Multiple Resource Theory approach to calculate workload, and expresses this as a graph of workload against time.

##### **3. Input Requirements**

Required tasks; Air traffic scenarios; other data files; video recordings etc...

#### **4. Outputs**

Graph of workload against time.  
Graphical simulation of activities with timelines.

#### **5. Major Assumptions**

Unknown

#### **6. Computational Characteristics**

PUMA is built on top of a proprietary object-oriented modelling environment (Lisp-based) and runs on Unix workstations and Mac workstations.

#### **7. Modularity and Flexibility**

Unknown

#### **8. Status**

The latest version is 2.2b. Roke Manor Research licences the system to third parties, as a fully supported product as well as supporting NATS's use.

#### **9. Extent of Model Verification**

Unknown

#### **10. Principal Applications**

PUMA has been used for UK ATC studies, and also under contract to Lfv (the Swedish CAA) to analyse the complete Swedish ATC system (tower, TMA and en route), and licences have been taken by Spain (AENA, the Spanish CAA), and Eurocontrol.

AENA (The Spanish CAA) has been working with RAMS for enroute studies. For workload analysis purposes, PUMA was hooked to RAMS the following way: RAMS was run normally. Each time a controller activity is generated in RAMS, it is sent to PUMA as a PUMA event. RAMS was suitably modified to detect task triggers.

PUMA has also been used for non-ATC purposes. In principle it's applicable in any area where tasks can be well defined, and the resulting workload needs to be determined.

#### **11. Availability**

Roke Manor Research (a contract R&D company, part of the Siemens organisation) developed PUMA for NATS during 1993, and have been developing it for them under contract since. The latest version is 2.2b. Roke Manor Research licences the system to third parties, as a fully supported product.

## **12. Information for Model Evaluation**

Paul Day  
Principal Account Manager  
Roke Manor Research  
e-mail: Paul.Day@roke.co.uk

Rob Whitaker  
CAA/NATS Air Traffic Management Development Centre  
Hurn, UK  
e-mail: robw@dasr.demon.co.uk

## **13. Summary Evaluation**

PUMA is a method and toolset for finely detailed modelling of human workload. It was developed for NATS for their work on future upgrades to NERC (New En Route Centre, the en route air traffic control centre for the London FIR). NERC will have its capacity enhanced by the provision of computerised support tools for the controllers, and NATS needed a desktop system to evaluate and filter out ideas, in terms of their effect on controller workload.

PUMA is a means of expressing controller tasks, defining a scenario of aircraft movements, and calculating the workload that results as the scenario plays through and the tasks are executed (and then altering tasks, repeating the calculation, and seeing the changes in workload). It uses the Wickens Multiple Resource Theory approach to calculate workload, and expresses this as a graph of workload against time.

PUMA is a suite of integrated tools, supporting a range of functions including task analysis (including the analysis of video recordings - it has a fully integrated video analysis system), task synthesis, scenario definition, task sequence definition, and workload calculation.

## 5.0 COST/BENEFIT ANALYSIS MODELS

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### 5.1 Review of Cost/Benefit Analysis Models

#### 5.1.1 Definition

A new development or modification of the ATM system, such as Free Flight, is only likely to be carried to fruition if some substantial benefits can be anticipated as a result of its implementation. In addition to benefits there will also be costs that inevitably accrue during both the implementation stage and in subsequent operations as well. If objective judgments of worth are to be made, in the process of deciding whether or not to proceed with implementation, the new development or modification should be evaluated by comparing some quantitative measures of the anticipated benefits against the projected costs of implementation. Also, both the non-recurring costs of development and the recurring costs of operation should be accounted for as well as the time sequencing of costs and benefits as they might accrue.

Cost/benefit models are a means by which quantitative projections of both costs and benefits can be realized. In particular, appropriate cost/benefit models can permit the extrapolation of costs over time as well as projections of financial measures of the benefits that may be expected. Hence, appropriate cost/benefit models can provide the objective means for judging the net worth of proposed new developments or modifications of the ATM system.

#### 5.1.2 Cost/Benefit Models

There is only minimal general-purpose capability currently available for cost/benefit analysis of the ATM system. Two models were identified that apply to this area, and only one of these is at a level of maturity that would enable it to be exercised by a user. Each model will be discussed in turn.

1. ACIM (Air Carrier Investment Model): This model, a part of NASA's ASAC (Aviation Systems Analysis Capability) initiative, generates estimates of the future demand for air travel from supply and demand factors based on projections of future economic conditions and operating characteristics of air carriers. From these the model creates estimates of future airline industry economic conditions, aircraft industry production demands and other economic parameters related to the economic health of both the airline and the aircraft industries. Examples of some typical economic parameter forecasts that can be created using the model are: 1) domestic and international travel demand in terms of revenue passenger miles, 2) the associated operating margins for air carriers, and 3) the total projected air carrier fleet size. The model will forecast these types of variables under various scenarios such as high economic growth and low unemployment, an oil price shock, and/or a fare war.
2. NARIM: This model is currently in its initial phase of development at the FAA. A primary goal of the effort is "to provide an analysis framework that enables the assessment of the operational, investment

and architectural implications of new operational concepts from the perspectives of the integrated aviation community” [1]. NARIM is best characterized as a modeling framework into which existing models will be integrated and combined with new models to permit extensive evaluations of new ATM concepts or modifications. It is intended to take maximum advantage of the modeling capability that already exists in the areas of airport and airspace operations simulation, conflict resolution, workload measurement, and human factors. Four functional areas will be addressed by the prototype-1) schedules and trajectories, 2) temporal mapping, 3) resource loading, and 4) performance and benefits analysis. Many existing models will be used either directly or in modified form to create the capabilities required in the first three areas. Extensive new modeling effort is anticipated in the fourth area.

### **5.1.3 Model Comparisons, Effectiveness and Validity**

The most significant differences between ACIM and NARIM are their relative level of maturity and the scope of their capabilities. ACIM is quite mature and has been in use for about four years. Its implementation is in the form of either a Lotus 1-2-3 or an Excel spread sheet. The program is quite user friendly and can be readily exercised after studying the associated User's Guide for a few hours, assuming modest knowledge of the Lotus 1-2-3 or Excel software application programs. In contrast, the NARIM model is under development and not available to potential users at the present time.

ACIM is an effective tool for projecting growth and demand in both the airline and commercial aircraft industries. The model utilizes high level economic parameters (such as population growth, fare yields and fuel prices) as inputs, to create projections of future air travel demand and airline cost functions. The model accounts for future productivity growth through projections of both human productivity enhancement factors and equipment efficiency gains. Human productivity gains are accounted for through reductions in labor price parameters over time. The model also predicts airline costs using parameters representing the aggregate characteristics of airline fleets and other factors to describe airline networks. The projections of air travel demand and airline costs are then combined in the model to create industry-level forecasts of future revenue passenger-miles, number of aircraft in the US fleet and airline operating margins. The model is particularly useful for evaluating the projected economic benefits that could be expected as a result of improvements in equipment efficiency or modifications of operating procedures that might be achieved from the introduction of new technology.

ACIM's validity rests on the extensive historical data bases from which it was created including the US Department of Transportation's (DOT) Origin and Destination (O&D) data record and airline cost data from DOT Form 41. The O&D data, as well as Census Bureau data on the economic characteristics of Standard Metropolitan Statistical Areas surrounding 85 major airports, were used to model the air travel demand for each of 13 US passenger air carriers (and/or their various manifestations through mergers and acquisitions) from 1970 to 1990. Similarly, the Form 41 data and other sources provided information for cost models for each of the 13 air carriers.

The ACIM model accurately portrays the recent history of economic evolution of the airline industry by capturing the data history in relatively simple regression models. The user supplies inputs which characterize a future economic supply and demand situation at high levels and the model projects the airline and aircraft industry economic situation from these inputs using its econometric models. Hence ACIM is an accurate extrapolator of current industry characteristics, which allows a user to explore the consequences of assumed future economic conditions and industry characteristics through judicious choices of input variables.

Because the NARIM model is currently only in the development stage it is not possible to evaluate its effectiveness and validity in a fashion similar to the evaluation of ACIM. However, the goals that it aspires to suggest that, if successfully developed, NARIM will provide capabilities which are more extensive than those of ACIM and which will address many current needs in terms of cost/benefit analysis as well as many other areas of evaluation of ATM concepts

#### **5.1.4 State of the Art of Cost/Benefit Modeling**

To effectively characterize the current state of the art in cost/benefit modeling of ATM it is important to first understand the need for this class of models. In evaluating any new ATM system concept it is important to balance the estimated costs of implementation and operation against the expected benefits. The timing of costs and benefits must also be accounted for since costs are likely to be paid initially, while benefits are typically received over the long term. This calls for the use of appropriate discounting practices that render "commensurable" dollars expended or received at different times

Although it is likely to provide useful results in a variety of contexts, cost/benefit modeling will be particularly important for evaluating the various manifestations of Free Flight that are likely to emerge in the future. For example, the current Free Flight concept envisages a major change in the way Traffic Flow Management (TFM) is executed for flights into major hub airports. It is likely that there would be considerable benefit if increased landing capacities are realized but, absent such an increase, any benefit in this area must presume that the current approach for executing TFM in the USA is inefficient; and that the new TFM approach, under Free Flight, will eliminate these inefficiencies. Evaluating this conjecture requires a definition of exactly how the old and the new TFM methods would work, studies to document the current TFM problems at major hubs, and the capability to evaluate performance and costs.

Similarly, the current Free Flight concept envisages an adaptive sectorization whereby sector sizes and manning can be quickly redefined to allow a re-routing of enroute flows around weather, etc. so as to avoid violations of sector workload limits. There is currently a re-routing tool available, called Automatic Demand Resolution (ADR), which has the potential to re-rout traffic equitably subject to sector workload limits. This new tool should be studied to see if the inherent problems in training controllers to work in an adaptive sectorization mode are worthwhile.

Cost/benefit analysis will be the primary tool for evaluating effectiveness of this approach.

As the Free Flight ATM concept evolves, each new concept is likely to require evaluation in terms of costs and benefits. Three main categories of participants are likely to receive significant benefits and incur costs from changes in the ATM system. They are:

- a) Aircraft Operators (Airlines, General Aviation, Military)
- b) Airline Passengers/Shippers
- c) ATM Service Provider

Each may receive different types of benefits and each will incur costs in a different fashion. A correct accounting should determine both the costs and benefits attributable to each category of participant. For example, a new or modified ATM system is likely to involve investments in both ground-based and airborne equipment. Typically, ground-based equipment costs will be borne by the ATM service providers, while airborne costs must be absorbed by aircraft operators. In corresponding fashion, other costs such as personnel training, system maintenance, software costs etc. will accrue to ATM providers or aircraft operators according to their respective roles in the ATM system.

The benefit most likely to accrue from a new ATM system, such as Free Flight, is time savings which will result from increased capacity of the ATM system. For air trips between certain terminals, in today's ATM system, there are built-in time delays due to capacity constraints at peak traffic times. In this context, time delay is defined as the excess time to accomplish a trip, over the trip time for a traffic-free flight.

Increasing the capacity of the ATM system should allow a direct decrease in the aggregate delays currently imbedded in nominal schedules as a result of capacity constraints at peak traffic times. For aircraft operators, time savings translate into reduced fuel and marginal aircraft operating costs, reduced interrupted trip expenses, and reduced costs for irregular operations. For passengers, the time savings should be translatable into equivalent cost savings. For business travel it is likely that this time-to-cost-savings translation can be accomplished rather directly through personnel costing. For personal and pleasure travelers the translation is more subjective and may require some form of rationalization to relate time delays to equivalent costs.

When viewed in the context of these needs it is clear that the existing models have limited capability and there is considerable need for new models. Table 5.1 illustrates the various categories of need for cost models and the ability of current models to fulfill the need. As can be seen, only the commercial air carrier category is supported in the capital, operating cost, and delay cost areas and, as indicated by the (+) signs in the boxes, additional modeling effort will be required to adapt ACIM so that it could appropriately satisfy the requirements in these areas. New modeling efforts are required to satisfy the needs in the other areas.

**Table. 5.1 Model Requirements**

<b>Cost Category</b>	<b>ATM Service Provider</b>	<b>Commercial Air</b>	<b>Military Air</b>	<b>GA</b>
<b>Capital Costs</b>	Need Model	ACIM(+)	Need Model	Need Model
<b>Operations Costs</b>	Need Model	ACIM(+)	Need Model	Need Model
<b>Delay Costs</b>	Not Applicable	ACIM(+)	Need Model	Need Model

### 5.1.5 Recommendations

As discussed earlier, there are three categories of participants in the ATM system who can reap benefits and/or incur costs. A cost/benefit model toolkit should include capabilities to analyze costs and benefits for each of these participants. The following sections summarize the identified modeling needs for each of these categories.

ATM Service Provider Cost Models: The costs which must be borne by the ATM provider are likely to constitute a major portion of the total expense incurred using any new ATM concept. Non-recurring costs will accrue for capital equipment expenses for the initial development and construction of facilities as well as the initial training expenses necessary to implement the concept. Recurring costs will accrue for operations and maintenance personnel, replacement equipment, and continual training of personnel to maintain proficiency. For any particular ATM concept, models will be necessary to allow the evaluation of costs incurred in relation to the benefits that may accrue as a result of implementing the concept. These models should allow the incorporation of projected growth of traffic and the associated required upgrading of the system over time.

As discussed above, such items as the cost aspects of traffic flow management and of adaptive sectorization must be included if Free Flight is to be effectively evaluated. An area of particular importance will be costs and potential savings that may accrue due to partial automation and operator assistance. Models must be capable of quantifying the tradeoffs between partial automation, operator assistance and manual operation of various elements of any ATM concept.

Aircraft Operator Cost Models: The operators of aircraft (Airlines, Military, GA) are likely to be the major beneficiaries of any new ATM concept and cost models of these constituencies will be necessary to quantify projections of benefits and costs. Models for airline personnel costs and marginal aircraft operating costs are the most readily available of these three categories. These cost models must facilitate the evaluation of airline operator cost savings resulting from reductions in delays attributable to ATM capacity increases. Models for military and GA costs/benefits will be more difficult to realize and are likely to be more subjective in nature. Additionally, all models must quantify the capital expense of new airborne and ground based equipment required to allow aircraft operation in any new ATM system, as well as recurring costs for maintenance and personnel training.

The ACIM model discussed earlier embodies much of the required capability needed for airline cost modeling, although the current implementation of ACIM may not provide some of the data outputs which might be desired in specific studies of airline costs. Certainly, any model development in this area should take advantage of the considerable expertise already embodied in ACIM and should build on the existing capability. For military and GA costs, new models will be required.

Currently missing from the ACIM model is the capability to evaluate the cost savings that might accrue due to reductions in travel times or airport delays. Such capability could be realized by augmenting ACIM, and/or creating a companion capability, to model delays and their effects on operator costs. The current ACIM structure is likely to be amenable to such an augmentation of its capabilities and the result is likely satisfy the need for effective evaluation of operator benefits which would result from Free Flight or other changes in ATM operations.

Passenger/Shipper Cost Models: As discussed earlier, it should be possible to create cost models for business travelers directly from personnel costs attributable to delays. Similarly, cost models for shippers should reflect the marginal costs for shipping that accrue as a result of delivery guarantee costs and/or personnel expenses which result from delayed shipments. In addition, some means of quantifying equivalent costs for personal and pleasure travel must also be determined. These costs are far more subjective in nature and not as readily and objectively defined as for business travelers and shippers. Models which facilitate parametric studies over ranges of possible values may be the most useful approach for these classes of travelers.

Common Requirements for Models: All of the cost/benefit models should be capable of and/or adaptable to both deterministic and probabilistic studies. In many instances there will be a need for a direct evaluation of costs based on a specific set of parameters. For example, an aircraft operator model should be capable of determining the change in marginal costs for a given airline which result from an ATM capacity increase for a specific trip between two cities. In addition, the aircraft operator model must also be able to create statistical estimates of relevant costs. An example here might be the determination of the expectation of future dollar savings for all airlines operating in a Free Flight environment. In this instance the model would incorporate probabilistic models of weather, economic forecasts over both time and geographical regions, and possibly projections of technical capabilities and costs affecting levels of automation for the ATM system concept.

To be most useful cost models should be amenable to integration with other models. For example, the conflict models described earlier are essential for quantifying capacity increases that may be achievable with any particular ATM concept. The cost models described in this section create the relationships between capacity increases and cost benefits to various constituencies. Implicit here is the need for a framework or medium to facilitate the integration of the various types of models. Such a framework would establish the initialization and information transfer facilities between models necessary for the wide range of tradeoff studies which are likely to be required to evolve a truly effective ATM concept. This integration

framework must function much like a modern computer operating system, creating appropriate user interfaces, managing resources, facilitating interchange of information and creating an appropriate environment for effective utilization of the various models and associated data bases.

The planned development of NARIM addresses many of the needs for integration of models. The NARIM development plan makes specific reference to maximizing the utilization of existing models to create a cost/benefit modeling capability. Hence the concept of NARIM itself embodies the need for effective integration of numerous models.

Finally, it is important to identify the need for models of varying simplicity and/or accuracy. Many issues can be addressed and questions successfully answered with relatively simple models which are inexpensive to both develop and exercise. Conversely, there are also instances when only extensive, detailed and more expensive models will suffice. Hence there should be at least two levels of modeling detail available for users. One level of modeling fidelity should be capable of quickly and efficiently answering questions at a rough order of magnitude level of accuracy, consistent with determining overall feasibility and direction for a concept. A second level of capability should be capable of answering more extensive questions at a much higher level of accuracy, consistent with detailed planning and scheduling of a new implementation.

## **Reference**

1. Bradford, S. and W. Colligan, "National Airspace Resource Investment Model: Needs Analysis and Operational Concept Report", Draft Report, Federal Aviation Administration, April 1996.

## 5.2 Reviews

### 5.2.1 ACIM: The ASAC Air Carrier Investment Model

(Last update: October 8, 1996 )

#### 1. Primary Model Category

Cost/Benefit and Investment Model

#### 2. Summary

ACIM is a tool for projecting growth and demand in both the airline and commercial aircraft industries. The model utilizes high level economic parameters (e.g. fare yields, population growth and labor costs) to create projections of future air travel demand and airline cost functions. It also accounts for future productivity growth through projections of both human productivity enhancement factors and equipment efficiency gains. Human productivity gains are accounted for through reductions in labor price parameters over time. The model also predicts airline costs using parameters representing the aggregate characteristics of airline fleets and other factors to describe airline networks. The projections of air travel demand and airline costs are then combined to create industry-level forecasts of future revenue passenger-miles, number of aircraft in the US fleet and airline operating margins. The model is particularly suitable for projecting the economic benefits that could be expected as a result of improvements in equipment efficiency or modifications of operating procedures that might be achieved from the introduction of new technology.

The ACIM econometric models are created from a number of databases including the US Department of Transportation's (DOT) Origin and Destination (O&D) data record, airline cost data from DOT Form 41, and Census Bureau data on the economic characteristics of Standard Metropolitan Statistical Areas surrounding 85 major airports. The O&D and Census Bureau data were used to model the air travel demand for each of 13 US passenger air carriers (and/or their various manifestations through mergers and acquisitions) from 1970 to 1990. Similarly, the Form 41 data and other sources provided information for cost models for each of the 13 air carriers. Included in the cost models are each carrier's labor costs, the characteristics of its network and its fleet characteristics in terms of numbers and size of various aircraft and efficiency factors for each type of aircraft.

ACIM's validity rests on the extensive historical data bases from which it was created. It accurately portrays the recent history of economic evolution of the airline industry by capturing the data history in relatively simple regression models. The user supplies inputs which characterize a future economic supply and demand situation at high levels and the model projects the airline and aircraft industry economic situation from these inputs using its econometric models. Hence ACIM is an accurate extrapolator of the current industry characteristics, which allows a user to explore the consequences of assumed future economic conditions and industry characteristics through judicious choices of input variables.

### 3. Input Requirements

The user inputs a series of values which project future annual changes in:

- Demand Variables-fare yield, national income, population growth, and unemployment rate
- Supply Variables-labor, energy, materials, and capital costs
- Network Factors-stage length and load factor
- Capital Attributes-average seats/aircraft, aircraft age, % jet aircraft, % wide body aircraft

Airline target operating margins over future time may also be input.

### 4. Outputs

The program outputs are future projections of:

- Domestic and international travel demand for U.S. scheduled passenger air carriers in revenue passenger miles
- Size of the total U.S. scheduled passenger air carrier fleet in numbers of aircraft
- Operating margin for U.S. scheduled passenger aircarrier fleet in percent

### 5. Major Assumptions

ACIM is based on the assumption that a model, based on data over the period of 1979 through 1990, can be used to create credible estimates of future conditions for the airline and aircraft industries. The validity of this assumption is, to a large extent, dependent upon the quality of the information used to create the model.

The model projects air travel demand forward using a regression model created from past information. Data for the demand model is based on the U.S. Department of Transportation's Origin and Destination record for tickets; coupled with the size and prosperity of the air travel market, inferred from standard economic models for regions surrounding 85 airports. Similarly a cost model was developed to account for labor, energy, materials and capital for 13 U.S. air carriers and/or their evolved manifestations in the period from 1979 through 1990. The primary capital element in the model is aircraft and aircraft productivity factors (e.g. increased fuel economy) are specifically accounted for in the model. Two additional factors, average stage length and passenger load factor, are used to model the effects of each air carrier's network characteristics on costs.

The demand and cost models are configured so that demand and costs can be projected forward in a fashion such that future total industry travel demand, air fleet size, and operating margin can be calculated.

## **6. Computational Characteristics**

The model has been implemented as a spread sheet and is available to run as an application program on either Lotus 1-2-3 or Microsoft Excel. Most current personal computers are capable of running the program.

## **7. Startup Effort**

The model can be used after only a few hours study of the users guide.

## **8. Modularity and Flexibility**

The program was written to produce some rather specific outputs from a set of input variables. Deviations from this specific set of input and output variables would require reprogramming of the model.

## **9. Status**

The model has been developed and tested extensively.

## **10. Extent of Model Validation**

The model is an accurate replica of past performance and conditions for the U.S. airline industry. Its validity for projecting future conditions in the industry depends upon a continuance of these same kinds of economic conditions in the future.

## **11. Principle Applications**

The principle application of the model is to study the relative advantages which new aircraft technologies can bring to the airline and aircraft industries.

## **12. Availability**

Upon request to Peter F. Kostiuk, Logistics Management Institute

## **13. Information for Model Evaluation**

Model description, users guide, and exercise of the model

## **14. Contact Point**

Peter F. Kostiuk  
Logistics Management Institute  
2000 Corporate Ridge  
McLean, VA 22102-7805  
Phone: (703) 917-7427  
Email: pkostiuk@lmi.org

## 15. Summary Evaluation

ACIM was specifically developed as a tool for estimating the relative benefits that might accrue to various new technologies which might be developed to increase the efficiency and/or productivity of future aircraft. Hence, ACIM is not a cost/benefit model as such, but might better be characterized as a module that could be embedded within a larger cost benefit model for the purpose of calculating airline industry supply/demand variables. The model is very easy to use and requires only minimal learning effort on the part of a new user.

### 5.2.2 NARIM: The National Airspace Resource Investment Model

#### 1. Primary Model Category

Modeling and analysis of future aviation system concepts

#### 2. Summary

The purpose of the National Airspace Resource Investment Model (NARIM) is to provide NASA and the FAA with the modeling and analysis capability to analyze airspace concepts associated with future advances to the National Airspace System (NAS). The system is being developed to also provide a NAS perspective to the research and investment allocation process. In providing this perspective, NARIM is to include the modeling and analysis of current and potential operations, the engineering impacts of future systems and the ability to trade requirements within a system and across systems and procedural investment alternatives.

The NARIM system consists of three interrelated parts:

1. Operational modeling to analyze the movement of aircraft through the NAS to determine the impacts that new concepts will have on the overall performance of the NAS.
2. Architectural or technical modeling, implemented through a series of executable engineering modeling capabilities, provides a means of assessing how procedural/system changes affect the hardware/software components of the NAS infrastructure (both FAA and users). This element of NARIM also provides an understanding of how the NAS components interact with each other based upon their performance characteristics and the flow of communication, navigation and surveillance (CNS) data and potential decision support system solutions between them.
3. Investment analysis modeling provides the user with a methodology to cost effectively trade between alternatives for a system, trade requirements within a system and across system and procedural investment alternatives, trade between services to be provided/included into the NAS, balance risk, and assess the investment decision as a of part of a total research portfolio.

Figure 5.1 provides a high-level functional flow diagram for NARIM.

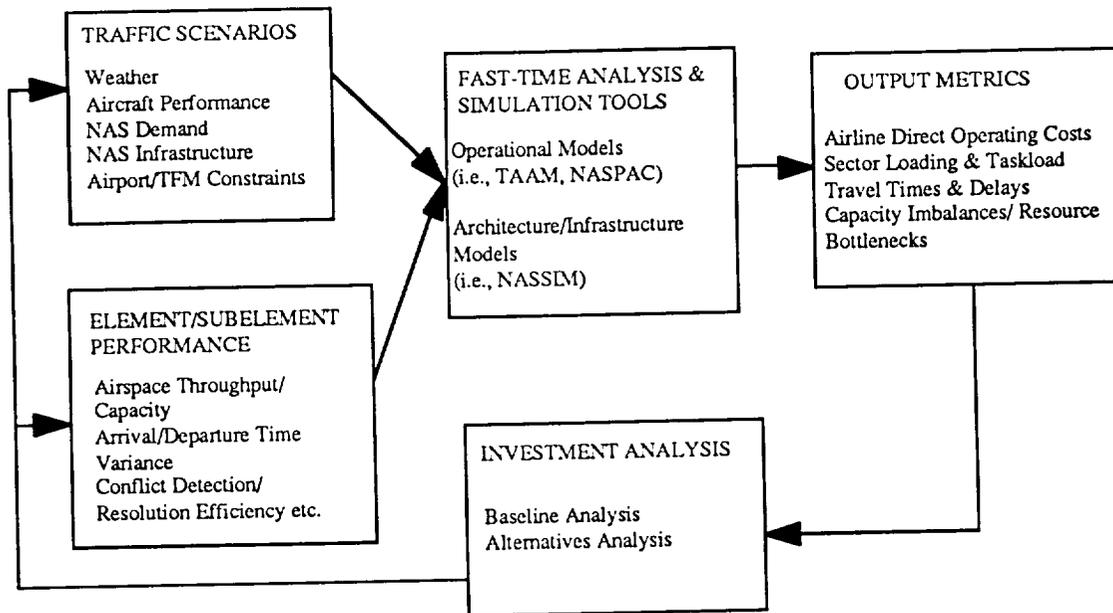


Figure 5.1 - NARIM Functional Flow Diagram

NARIM is being built incrementally through a series of three builds. The first build, the NARIM prototype, has been completed and is currently being applied by the FAA's Program Analysis and Operations Research Division for a study of NAS and ETMS data variability. The NARIM prototype analysis capability is based on four functions: schedule and trajectory generation, temporal mapping to the NAS, NAS resource loading simulation, and NAS performance and benefit analysis.

Builds 2 and 3, which have not yet been initiated, will implement a large number of enhancements and new capabilities.

### 3. Input Requirements

NARIM input requirements will vary depending upon the particular analysis being performed. They include: for operational analysis inputs on weather, aircraft performance, NAS infrastructure data, NAS demand and airport/TFM Constraints; for architecture and infrastructure analysis inputs on NAS subsystem performance characteristics, NAS infrastructure data, spatial/temporal flight mapping; for investment alternatives analysis inputs on conflict potential, sector loading, workload and resource demand/capacity imbalances.

### 4. Outputs

NARIM output metrics vary depending upon the particular analysis being performed. They include: for operational analysis outputs about sector loading, travel times, assigned delays, en route/arrival/departure delays, workload, conflict potential and conflict analysis; for architecture and

infrastructure analysis outputs on resource demand/capacity imbalances; for investment alternatives analysis outputs on numerous metrics such as cost by airline/airframe, time savings, fuel savings, direct operating costs, levels of safety, controller workload, etc.

## **5. Major Assumptions**

NARIM analyses will be drawing on the capabilities of a large set of constituent models. Therefore, the major assumptions made in each analysis will reflect the assumptions inherent in the particular set of models (e.g., RAMS, TAAM, etc.) which will be utilized in each specific case.

## **6. Computational Characteristics**

The NARIM prototype currently consists of three independent, stand-alone software elements. Of these, the most mature is the operational modeling element, consisting of several stand-alone software modules integrated through data. These software modules reside on a workstation running the UNIX OS and are written in C and C++. NASSIM, the prototype architecture/infrastructure model resides on a Power PC-based Macintosh computer and is written in Extend™, a COTS simulation development environment. The IRSM methodology tool is hosted on a Pentium-based PC running the UNIX OS and is developed in XRT-3D

## **7. Modularity and Flexibility**

The design approach undertaken for the NARIM prototype development was to provide reusable software components based predominately upon ASD analysis tools; existing and on-going research initiatives sponsored by ASD. In addition to minimizing prototype development time and risk, this design approach will ensure that NARIM is modular and extendible, providing long term benefit to the FAA and the NASA through software reuse as well as provide immediate utility to both organizations near-term analysis needs. The long-term result of this approach will be development of an analysis framework in which individual components may be configured to support timely multi-dimensional analysis of a multitude of diverse aviation issues.

## **8. Status of Model**

The model has completed the first of three planned builds. At this time, NARIM documentation is not sufficient to support replication of the model and distribution to other organizations. Since integration within the current prototype is through data, current users of NARIM are restricted to software developers.

## **9. Extent of Model Validation**

Since NARIM input consists of actual FAA operational data (such as ACES, ETMS, NAS subsystem performance characteristics ) the input data sources should require no further validation. The model components are

being validated as a part of the ongoing analyses being performed as a part of the NARIM rapid prototyping effort.

## **10. Principal Applications**

The principal applications of NARIM are associated with the modeling and analysis of airspace and aviation concepts for future development. NARIM is being developed to assist the FAA and the NASA in the research and investment allocation process.

## **11. Availability**

Upon request to Dr. Mark Rodgers, FAA/ASD-430, Federal Aviation Administration, 800 Independence Ave., SW, Washington, DC 20024. Phone: (202) 358-5372. Email: mark.rodgers@faa.dot.gov

## **12. Information for Model Evaluation**

NARIM Needs Analysis and Operational Concept Report, April 1996

## **16. Summary Evaluation**

The purpose of the National Airspace Resource Investment Model (NARIM) is to provide NASA and the FAA with the modeling and analysis capability to analyze airspace concepts for future development. The system is being developed to also provide a National Airspace System (NAS) perspective to the research and investment allocation process. In providing this perspective, NARIM is to include the modeling and analysis of current and potential operations, the engineering impacts of future systems and the ability to trade requirements within a system and across system and procedural investment alternatives.

Due to lack of experience to date it is premature to attempt any evaluation of NARIM's strengths and weaknesses, even with regard to its first "build". Undoubtedly, NARIM, as a concept, represents one of the most ambitious ATM model development projects ever undertaken.

## **6.0 NOISE Models**

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### **6.1 Review of Noise Models**

This brief section provides individual reviews for two noise models, INM (The Integrated Noise Model) and NOISIM, a model developed very recently at MIT for the purpose of providing highly detailed analyses of single noise-generating events due to arrival or departure of an aircraft at an airport. These two models are outside the main scope of this study and the two reviews below have been prepared only for the sake of providing information to potential noise model users.

### **6.2 Reviews**

#### **6.2.1 Integrated Noise Model (INM), Version 5.0 (FAA)**

(Last update: 8/29/96 JKK)

##### **1. Primary Model Category**

Modeling and Display of Aircraft Community Noise Impact.

##### **2. Summary**

INM is an empirical tool used to calculate the noise impact around airports. The noise levels are based on a series of stored noise profiles of different aircraft under different flight conditions such as weight and trip length. The model has recently been enhanced (Version 5.0) to include a number of new capabilities.

##### **3. Input Requirements**

Requires an aircraft flight profile, including aircraft type, flight plan, and trip length (gross weight). Data may be entered using a graphical user interface using Windows. Geographical Information System (GIS) overlays can be used to show impact on population and topography. The model includes navigational aid data for the entire U.S. and can also incorporate ARTS radar data to examine actual trajectories. Official Airline Guide (OAG) data can also be used to examine traffic schedules and fleet mixes.

##### **4. Outputs**

A Graphical User Interface is also used for analysis of the results. INM displays the community noise impact as a series of noise contours in Noise Exposure Forecast (NEF), Equivalent Sound Level (Leq), Day-Night Average Sound Level (Ldn), and Time Above a specified threshold of A-Weighted Sound (TA). The model calculates the total area exposed to different noise levels, and the population exposed to different noise levels. A differencing feature is included to allow the comparison of two different operating conditions on noise impact.

## **5. Major Assumptions**

The trajectory of the aircraft can be modeled as a series of straight and constant-radius curved segments or can be specified using actual ARTS data or through OAG schedules. Noise information is stored as intensity directly below the path of the aircraft. Sideline noise measurements are calculated using a lateral attenuation factor that is a function of the aircraft's height and azimuth above the ground. The model can be used to examine single or multiple events, and can include lateral dispersion of flight tracks. Wind is not included as a parameter.

## **6. Computational Characteristics**

Code exists for Windows NT (recommended) and Windows V3.1 for PCs. Minimum specifications are: 486DX 66MHz processor, Microsoft Windows NT (V3.5) with 35 MB RAM or Windows V3.1 with 16 MB RAM, 640x480 16 color VGA display, mouse input device, 3.5" 1.44 MB floppy disk drive, 300 MB hard drive (INM requires 20 MB, each study requires 1-30 MB), CD-ROM drive for terrain and census data processing (optional).

## **7. Modularity and Flexibility**

INM is a stand-alone analysis tool and would not be easily ported or incorporated in a larger software package.

## **8. Status**

The model is the FAA standard for calculating aircraft noise impact.

## **9. Extent of Model Verification**

The empirical data used in the model has been verified through an extensive testing program.

## **10. Principal Applications**

Calculation of the noise impact (in terms of area and population) for a single aircraft for a single event or a mix of aircraft over an extended period. Includes lateral dispersion of flight tracks, flexible aircraft profile generation, graphical track construction, and expanded visual analysis.

## **11. Availability**

Available for \$250 from the FAA. Contact: John Gulding, INM 5.0 Program Manager, (202)-267-3654.

## **12. Information for Model Evaluation**

User's Guide for INM (V3.0); V 5.0 press release; communication with Donna Warren, FAA.

## 13. Summary Evaluation

INM is the FAA standard noise prediction tool. It assumes that aircraft will fly trajectories that can deviate from specified flight plans or can use ARTS trajectory data. It is limited in its ability to predict the variability in noise impact that could occur due to wind conditions, but is flexible in terms of analyzing operating procedures and fleet mixes. INM has improved graphical interfaces for both data entry and visual analysis of the results.

### 6.2.2 NOISIM

(Last update: 5/13/96 JKK)

#### 1. Primary Model Category

Modeling and Display of Aircraft Community Noise Impact.

#### 2. Summary

NOISIM is a real-time aircraft simulator with the ability to model and display the community noise impact of a specific trajectory that is flown. The model implicitly includes any aircraft-specific constraints and also includes the effect of wind or other atmospheric conditions on aircraft performance and noise propagation.

#### 3. Input Requirements

NOISIM requires a pre-programmed flight plan or real-time procedure entry through a control display unit, mode control panel, keyboard, or manual stick inputs. A Graphical User Interface is used to plot and calculate noise impact. Flight plans can be pre-programmed using a text input file. Wind conditions can also be prescribed in a text input file. Changes in wind conditions can be scripted (e.g., to simulate windshear events).

#### 4. Outputs

NOISIM displays the community noise impact as a series of noise contours in A-Weight Sound Pressure Level (dBA) or Sound Exposure Level (SEL). These contours are overlaid on a map derived from USGS hydrography and land use data. The model calculates the total area exposed to different noise levels, the land area exposed to different noise levels, and the population exposed to different noise levels. Other derived metrics such as the Equivalent Sound Level (Leq) and Time Above a specified threshold of A-Weighted Sound (TA) can be calculated.

#### 5. Major Assumptions

The aircraft performance and engine parameters at each iteration step are calculated as if the engine is at steady state.

## **6. Computational Characteristics**

Code exists (written in C). Software has been developed for Silicon Graphics platforms. Documentation quality is currently in draft for the prototype version. Calculation of the noise impact takes 15-20 minutes of post processing computation.

## **7. Modularity and Flexibility**

The simulator allows rapid prototyping of different cockpit display, navigation systems, aircraft parameters, and engine parameters. It is currently configured with 737 performance and engine parameters, and 747-400 instrumentation. Modifications to the dynamic model may involve significant recoding. Topographical data for the Boston metropolitan area is currently included to determine land area noise impact. Noise calculation routines are modularized and can be separated from the aircraft simulation.

## **8. Status**

The model is intended as an experimental tool, is a first prototype, and is not mature. An extensive graphical user interface is in place and is easy to use for the display and calculation of noise impact.

## **9. Extent of Model Verification**

In a series of simulations designed to mimic the radar trajectory of a 737 operating out of Boston Logan Airport, the noise simulations agree to within 2 dBA with recorded data from noise monitoring stations around the airport.

## **10. Principal Applications**

Investigation of the trades between noise impact and aircraft performance. Development of prototype noise abatement procedures.

## **11. Availability**

Contact: John-Paul Clarke, MIT, (617) 253-7748, johnpaul@mit.edu, or Prof. R. John Hansman, MIT, (617) 253-2271, rjhans@mit.edu

## **12. Information for Model Evaluation**

Summary is based on a review by the author of NOISIM. No documentation is currently available.

## **13. Summary Evaluation**

NOISIM is a prototype version of an all-in-one aircraft noise simulator developed to investigate the trades between noise impact and aircraft performance, and evaluate prototype noise abatement procedures. The model has realistic flight dynamics and implicitly includes the performance constraints which limit the maneuvers that may be performed in a noise abatement procedure. It also provides researchers with a tool to determine

how piloted aircraft flight procedures affect the community noise impact. NOISIM uses actual piloted flight data to determine noise impact, rather than an assumed trajectory that is followed perfectly. Thus, NOISIM appears to be better able to show expected variations in noise impact due to aircraft tracking performance or wind conditions than the Integrated Noise Model (INM).

## 7. CONCLUSIONS AND RECOMMENDATIONS

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We present next the principal conclusions of this study and a related number of action recommendations. These recommendations are *in addition* to the numerous recommendations that have already been made in connection with improvements and further model development in the areas of capacity and delay modeling (Section 2), conflict detection and resolution (Section 3), humans / automation models (Section 4) and cost/benefit analysis (Section 5). Section 7.1 summarizes the overall conclusions with regard to the state-of-the-art in the various categories of ATM and airport modeling. Section 7.2 draws from these conclusions to articulate some overall policy guidelines that might inform future FAA and NASA policies regarding ATM and airport development. Finally, Section 7.7 presents an additional set of recommendations that span the specific categories of models discussed in Sections 2-6.

### 7.1 General Findings

One fundamental conclusion of our review is that the state-of-the-art varies considerably across the various categories of airspace and airport modeling. A ranking of the categories, from most advanced to least, would be as follows:

1. Capacity and delay models
2. Conflict generation, detection and resolution models.
3. Human factors and automation models.
4. Cost/benefit models.
5. Models of strategies and behavior of airlines (airline operations centers) and of other users vis-a-vis ATM.

As this ranking indicates, capacity and delay models are, in the view of the study team, the most advanced, in terms of being able to meet user needs. After more than three decades of work the “physical principles” of air traffic flows, capacity and delays are reasonably well understood. The family of existing models in this area has the ability, with proper use, to provide reasonably good estimates of capacities and delays for individual elements and even for groups of elements of the ATM system. Moreover, different models address these issues at different levels of detail (low, intermediate and high) and thus make it possible for informed users to select a model(s), and corresponding level of detail, most appropriate to their needs.

However, some serious deficiencies still remain. The best existing capacity and delay models still suffer --different models to different degrees-- in several fundamental respects that were discussed in Section 2. These deficiencies can be classified into a small number categories: lack of some essential features (e.g., stochasticity); lack of flexibility (e.g., a node-link structure); lack of mutual compatibility; poor user interfaces; and costly and time-consuming training, learning and input/experiment preparation requirements.

Conflict generation, detection and resolution models have attracted much attention in recent years, especially in connection with proposed new ATM concepts, such as Free Flight. Understanding of the fundamental issues in this area has improved considerably as a result and a number of models (Section 3) have been or are being developed that provide significant capabilities in this respect. However, in the view of the study team, *no single existing model provides enough flexibility and capability to perform a complete, in-depth study of conflict detection and resolution*. Each existing model lacks some or many of the features necessary for such a task.

The area of *fast-time* modeling of humans and automation in ATM (Section 4) is still in its early stages of development. We could identify only one general-purpose model (MIDAS) and very few special-purpose ones. While these provide a good starting point, much remains to be done. Many of the basic principles and issues in this area are not yet fully understood at the *conceptual* level. Given the immense importance of human factors/automation in the design and operation of any of the proposed advanced ATM concepts, this category of modeling deserves urgent attention and investment of adequate resources by the various national and international civil aviation authorities and organizations.

The state-of-the-art in estimating costs and benefits (Section 5) associated with advanced ATM concepts, such as Free Flight, is rather primitive at this time. Most of the available models deal with four metrics of ATM performance: capacity, delay, fuel consumption and workload (as inferred, for example, by the number of conflicts that must be resolved). But many of the potential benefits of proposed advanced ATM concepts, such as "safety", "increased operating flexibility for airspace users", "lower costs for ATM system operators" or "increased access to airports due to better navigation capabilities" are not captured in any way by available models. Moreover, our ability to estimate in economic terms the value of many of these costs and benefits still leaves much to be desired. Much basic research is needed in all these respects.

Only one general-purpose model, ACIM, in this area has (very recently) reached an adequate level of maturity. ACIM is a valuable tool for projecting the impacts of future changes in ATM- and airport-related costs on air transportation demand and airline growth and fleets. However, ACIM does not, of itself, estimate these airport/ATM costs, but must rely on other models to do so. A far more ambitious effort to develop an integrated suite of models, NARIM, that would guide ATM-related investments and support cost-benefit analyses has been launched by the FAA, but it is too early to judge its level --or, even, its prospects-- of success.

Finally, our examination of modeling needs for the evaluation of partially decentralized ATM concepts, such as Free Flight, has made clear the almost complete absence of any models that would assist ATM planners to predict airline and other airspace user strategies and behavior in such an environment. Free Flight and related concepts are characterized by the transfer of some or many decision-making responsibilities to airspace users and provide these users with increased latitude in planning and performing flights. Understanding how users, especially airline operations centers, would operate under such circumstances (including arrival and departure

slot utilization, allocation of expected delays between delays taken on the ground before departure and delays taken in the air, “gaming” to gain advantage over competitors, etc., etc.) is an essential element of our ability to assess and evaluate these new ATM concepts. The development of models that would make such understanding possible represents an entirely new area of basic research that has, all of a sudden, assumed major importance.

## 7.2 Strategic Guidelines for Future Work

The findings described in the last section and in Sections 2-6 have important strategic implications regarding future work on airport and ATM modeling. We present below a set of proposed policy guidelines to assist NASA and the FAA in this respect:

1. Not only strong enhancements to existing models, but also extensive new modeling capabilities will be needed in the short, medium and long term, to determine the feasibility and evaluate proposed advanced ATM concepts, such as Free Flight. In several cases, these new capabilities must go well beyond anything that exists today and will require work on understanding basic principles before modeling *per se* can begin. In view of the fact that assessment and evaluation of advanced ATM concepts has already started at the FAA and under NASA’s AATT concept, the development of the models must be undertaken immediately and in parallel. This is an *urgent* requirement: assessment and evaluation simply cannot be done in a credible way without the support of adequate and credible models.
2. The FAA and NASA should draw up a detailed plan for supporting model development and experimentation. This plan should be dynamic, i.e., it should not be “cast in concrete” so it can be revised appropriately over time to take into consideration successes and failures along the way. Adequate funding for such a model development program should be provided for. A conservative guess is that an amount of at least \$10 million per year over several years would be necessary to support a credible program of development, validation and experimentation with *fast-time* models. (This is in addition to the significant investments currently being made by both NASA and FAA in real-time, human-in-the-loop facilities.)
3. Drawing up such a program would be greatly assisted by the existence of a few well-defined strawman architecture(s) of advanced ATM concepts, such as Free Flight. Such architectures are currently in the process of being developed. They would be very useful in specifying the kinds of capabilities that existing, enhanced and newly-developed models should have and in setting priorities and allocating funding among alternative model-development paths.
4. Model development can be facilitated further through specification of model requirements with broad user participation. A good example of this approach is a recently formed, broadly-participatory group in Europe, whose objective is to develop a detailed set of specifications for future airport/terminal area modeling.

5. In allocating resources for future model improvement and new model development, it is important to recognize the need for:

(a) Modeling the ATM and airport systems at several different levels of and/or accuracy (macroscopic, mesoscopic, microscopic, in the terminology used in this report); the tendency to overemphasize microscopic models should be resisted.

(b) Databases and generic "utility" modules (see Section 7.5 below) that can be used to support many models in any given category.

6. It is important to recognize the synergisms and trade-offs between fast-time models, which are the subject of this report, and real-time, human-in-the-loop ones. It is, of course, true that many ATM concepts and changes cannot be validated without the eventual use of the latter. However, human-in-the-loop experiments are time-consuming and costly and the associated facilities very expensive. Fast-time models can be very effective as "filters" for eliminating large numbers of proposed alternatives before subjecting the remaining few to real-time tests. There are also certain types of issues (e.g., ones exploring capacity, delay and workload on a broader, sometimes system-wide basis) that simply cannot be investigated without the use of fast-time models.

7. Existing ATM and airport models to date have been primarily developed by ATM and airport specialists for whom software development has been a secondary consideration. As a result, the usability, robustness and user interfaces of many existing models are severely deficient. Much improved software engineering practices should be expected and required in the future.

8. Along similar lines, existing airport and ATM models are all essentially of the "passive" and "what if..." type: a hypothetical situation is posited and the model performs a simulation or similar analysis and provides a set of results. The model does not provide a diagnosis of any problems about the situation that has been analyzed or simulated --such as identifying the "bottlenecks" at an airport-- nor can it suggest alternatives for solving such problems (i.e., the model does not "optimize" in any sense). However, it is now technically feasible to add some such diagnostic and optimization capabilities to several types of models. This important type of improvement should be encouraged and explored.

9. Finally, in supporting future model development and allocating related resources, it is important to seek a proper balance between two fundamental strategies: (a) building new or improved models that address in a comprehensive manner specific domains (e.g., a better future model of all aspects of airport operations); and (b) developing "suites" or "toolkits" (in the NARIM or ASAC mode) of compatible models that can serve as "building blocks" to be assembled and configured, as needed, in addressing issues at hand. The viability and attractiveness of the second strategy has been greatly strengthened recently by the emergence of distributed simulation technologies.

### 7.3 Specific Recommended Actions

The principal recommendations of this study are that:

1. A model improvement and development program, consistent with the policy guidelines provided in Section 7.2 above, be undertaken by NASA and/or the FAA.
2. The numerous specific recommendations (about 25) made in Sections 2.1, 3.1, 4.1 and 5.1 be reviewed carefully as potential tasks to be carried out in connection with the recommended model improvement and development program.

In addition, the following potential areas of activity, which are not specific to any particular category of models, should be considered in connection with the proposed program:

(a) Better information for prospective ATM and airport model users: The most common and costly mistake of model users today is the selection of models which are not appropriate for their needs. An example, might be the use of a highly-detailed model, like SIMMOD or TAAM, to identify the time when significant expansion of an airport's capacity will be necessary. This is a "macroscopic" policy question which typically looks 10 - 20 years into the future. It should be answered with the help of an approximate, fast and easy-to-use model, not one that requires a detailed layout of the airport, the construction of highly detailed scenarios, which are subject to great uncertainty, and a (totally speculative) flight-by-flight demand schedule for the distant future. Similar examples abound.

Such mistakes are due to lack of information on the part of potential model users (including large government organizations) about what models are available (typically the potential user is aware of only a handful) and to lack of appreciation of the fact that the best model to use depends on what question is being addressed. There is therefore a clear need to educate potential users of ATM and airport models about:

- (i) model availability;
- (ii) model characteristics, especially their fundamental assumptions, limitations and level of detail;
- (iii) explicit and hidden costs (e.g., learning costs, limited technical support) associated with model use; and
- (iv) the proper criteria for model evaluation and selection.

The research reported here is a step in this direction. Other helpful information is available in a number of Web sites referenced in Appendix C.

(b) Integration of existing models: This point has been raised on several occasions in this report, but is worth repeating, because of its importance. Possibly the one most striking observation to emerge from this study concerns the lack of any semblance of compatibility among the many models reviewed. As a rule, existing models have been developed independently of one another, have different data needs and input and output formats and sometimes contain conflicting assumptions. This makes

it extremely difficult to conduct any systemic studies that examine at the same level of depth different elements of the ATM system or address a particular question at progressively greater levels of detail.

Yet, there are many cases in which it would not be particularly difficult to develop interfaces between existing models that would make it possible to move seamlessly from model to model and obtain an overall capability that is "greater than the sum of its parts". Several specific examples have been provided at various points in this document. Eventually such efforts could lead to the assembly of compatible "toolkits" of models such as the ones described in earlier sections. A major development of the last couple of years has indeed been the initiation of a few projects along the lines outlined above. For example, the TAPE project in Europe is attempting to integrate several airside (runways, taxiways, apron) and landside (passenger terminal) models of airport operations, so that the user can observe the effects of proposed airside changes or of airside congestion on passenger terminal operations and vice versa. Similarly, two other ongoing projects in Europe are developing interfaces between RAMS and, respectively, SIMMOD and PUMA. The ASAC and NARIM projects in the United States have even more ambitious long-term objectives concerning the development of compatible model suites. These efforts, we believe, reflect the growing international recognition of the need to improve model integration.

(c) "Utilities" and databases: In addition to developing better ATM and airport models, it is also very important to improve the supporting utilities and databases which are often required by these models in a wide variety of contexts. We offer several examples below.

There is a major requirement for "utility" programs that would facilitate the generation of (i) hypothetical demand schedules for ATM and airport facilities and (ii) representative weather scenarios. With respect to (i), practically all existing capacity and delay models require detailed, flight-by-flight schedule of demand over the course of a day of operations. In particular, network models such as NASPAC, AND and ASCENT that are concerned with operations over an entire system of airports and/or en route sectors also require flight *connections*, i.e., complete itineraries that indicate the route that each aircraft of an airline will execute on any particular day. Obviously, such detailed demand scenarios, especially the ones requiring complete aircraft itineraries, are not available for the future and have to be developed for use with network models. To our knowledge, only two such detailed demand generators are currently available. One is the Pseudo - Official Airline Guide Generator (POAGG) that has been developed at the Draper Laboratory to support ASCENT. POAGG uses a combination of heuristics and mathematical programming to create reasonably realistic flight schedules that satisfy user-specified parameters including: the number and hourly distribution of arrivals at each airport in a network; the percentage of flights that connect to each of the other airports in the network; the presence, if any, of shuttle flights between pairs of airports in the networks; and the presence, if any, of "banks" of flights at the hub airports in the network. The other such demand generator, with apparently similar characteristics, has been developed at MITRE CAASD for NASPAC. There is considerably more work that can be done to improve the state-of-the-art in

this area, and resulting programs, once tested and validated, should be disseminated widely, so they can support a wide range of models.

A similar need exists for "utilities" which will provide weather scenarios for use with a large variety of ATM and airport models. These include the generation of: simulated weather front and winds aloft scenarios for use with airspace models; visibility, ceiling, wind and precipitation scenarios for airports; and, most difficult, regional models that generate weather scenarios for several locations simultaneously and capture realistically the potentially strong correlation between weather conditions at geographically proximate airports (e.g., Washington, New York and Boston). The state-of-the-art is not particularly advanced in this respect, but a number of approaches have started to emerge in recent years. Examples include Markovian and semi-Markovian models to generate weather scenarios at individual airports and the U.S. Air Force's Sawtooth Weather Model for generating regional weather profiles. Considerable additional resources would need to be invested in this area.

Turning to databases, it is clear that there exists, once again an acute need for improvement. The ATM research and development community would benefit greatly from an effort aimed at assembling and maintaining a set of databases that would facilitate future modeling and simulation experiments and, equally important, make it possible to compare the results obtained from different models and approaches. Four obviously needed types of databases are:

- (i) "Standard day" scenarios for specific locations (e.g., terminal areas) or regions (e.g., Northeast United States, Western Europe) that include detailed information on traffic demand, weather, capacities achieved, delays, etc. on these days.
- (ii) Computer-coded airport layouts and airspace configurations, obtained from previously performed studies.
- (iii) Standardized set of performance characteristics for a large number of commercial and (possibly also) general aviation aircraft types.
- (iv) Inventory of airline costs, fleet composition, financial performance, demand, traffic growth, etc.

Much already exists in both areas (i) and (ii). For example, the FAA has used SIMMOD to simulate large portions of the U.S. airspace and, in the process, has developed detailed network representations of this airspace, some reportedly involving as many as 20,000 links. (More obviously, numerous airports in the U.S., Europe, Asia and Australia have been simulated with SIMMOD, The Airport Machine and TAAM, with much effort expended on coding the layouts of these airports for use with these models.) However, no organization to date has assumed or been assigned the responsibility for maintaining these data sets and making them available to other potential users.

In areas (iii) and (iv) the situation is more promising because of the growing international use of BADA as a source of commercial aircraft performance data and of the recently implemented LMI Air Carrier Investment Model (ACIM) as the source of airline-related data. Much, however, still remains to be done in both respects.

(d) Models of Airline Operations Centers (AOC) and of their interactions with ATM: As observed in Section 7.1, our examination of modeling needs for the evaluation of partially decentralized ATM concepts, such as Free Flight, has underscored the almost complete absence of any models that would assist ATM planners to predict airline and other airspace user strategies and behavior in such an environment. Yet, understanding how AOCs will interact with ATM in a more decentralized decision-making environment is essential to evaluating advanced ATM concepts of the future. Thus, the development of models that would make such understanding possible represents an important new area of basic research. We strongly recommend that such work be initiated immediately, in close collaboration with the airlines. Many discussions and contacts have made it clear that many AOC professionals already recognize the need for such work and would offer valuable support along these lines.

## Appendix A: Free Flight Case Study

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### 1. The Issues

This is a report on the first case study carried out under the MIT Model Review and Evaluation project undertaken in connection with NASA's AATT Program. This first case study is centered around the Free Flight concept. In particular we are concerned with *identifying and describing the kinds of modeling capabilities that one would need in order to analyze and evaluate the Free Flight concept.*

Based on a critical review of available materials prepared in October 1995 by the Steering Committee of RTCA Task Force 3 on *Free Flight Implementation.*, it is clear that the Free Flight concept is still in its formative stages. The driving motivation behind it is the desire to remove, to the greatest extent possible, the constraints currently imposed by ATM on flying under IFR, so that aircraft can take maximum advantage of rapidly improving aircraft-based capabilities. This calls for some fundamental re-thinking of the basic premises of the ATM system.

It is far from clear, however, that Free Flight can work in the presence of some of the severe capacity limitations that the ATM system is faced with, especially in major terminal areas and in less than ideal weather conditions. The extent to which Free Flight can be practiced at times when airport acceptance rates require the imposition of some controls on the flows of traffic remains an open question. A major restructuring of air traffic flow management might be called for.

On this crucial point, current thinking is to try to replace today's "controlled time of departure" (i.e., specifying when a flight operating under flow management restrictions will take off) by a "required time of arrival", RTA, which will specify when a flight has to arrive at a specific location. This location could be at a fix just outside the terminal area of the airport of destination or at some other point which, under circumstances of major congestion, could be several hundreds of miles away from the airport of destination. The idea, of course, is that each flight would determine for itself an "optimal" (according to some criterion) strategy (i.e., a 4-D trajectory) for getting at the specified point at the specified time. Each flight would use a "user preferred route" (i.e., a Free Flight path) to get from the airport of origin --or, from the boundary of the terminal area of origin -- to the location at which the specified RTA would apply. Thus, this approach would do away with the current use of en route "miles in trail" --or "minutes in trail"-- separations along standardized routes. However, it is still unclear how the "boundary conditions" imposed by congested terminal areas might impact (i) the extent to which optimal point-to-point trajectories could be utilized en route and (ii) the number and complexity of the conflicts between flight trajectories that would have to be detected and resolved in the airspace where Free Flight would be available.

A critical related question concerns the *robustness* of the traffic flow management scheme outlined above. The transition from Free Flight to a

“flow managed” regime in and near terminal areas would have to be accomplished smoothly, routinely and always safely in the presence of uncertainty. This uncertainty derives from at least three causes: (a) the variability in airport capacities due to fluctuations in traffic mix and attendant spacing between successive arrivals, as well as the mix and sequencing of arrivals and departures; (b) unexpected changes in airport acceptance rates due to weather variability, wind shifts, changes in runway configurations in use; and (c) short-term differences between predicted and actual airport demand, due to unanticipated flights (“pop-ups”), cancellations or diversions of flights, etc.

In summary, determining the workability of Free Flight requires a very extensive amount of analysis. This motivates the question we are addressing under this case study which can now be stated in the following terms: “Given Free Flight as a ‘generic’ concept, what kinds of models and tools would be necessary to assess its safety-related characteristics as well as its costs and benefits to ATM users (including passengers) and operators (including all those who pay for the ATM system)?” Fortunately, this question can be addressed without having to wait for the full definition of a future ATM system based on the Free Flight concept --a milestone which may still be some time away.

To make the task more manageable, it was decided to decompose the above question into four simpler parts, as follows:

(1) Optimal flight trajectories and planning: Assume, first, that there is only a single aircraft in the world. What kinds of models/methodologies would be needed for computing a 4-D “optimal” flight trajectory for that aircraft from origin to destination? (We leave unspecified here the definition of “optimal” and we presume that the question needs to be addressed under a variety of assumptions regarding aircraft capabilities, available information about weather/winds, frequency of information updates, etc.)

(2) Conflict frequency, detection and resolution: Assume next that each aircraft would fly independently its own optimal 4D trajectory and that there are no capacity limitations at airports. What kinds of models would be needed to evaluate the statistics describing frequency of conflicts and the associated levels of system integrity that would be generated by some given ensemble of aircraft, performing a given schedule of flights with a specified temporal and spatial distribution? (A “conflict” here is defined by a measure of spatial proximity and by some conflict geometry; “conflicts” may translate into “alerts”, pilot and ATC controller workload, etc.). It is also important to consider what kinds of models would be needed to design and evaluate conflict resolution systems that are used to separate aircraft once a conflict has been detected. For example, issues such as safety, false alarm rate, and the impact of conflict resolution on traffic flow will need to be evaluated.

(3) Operation under traffic flow limitations: Assume next that Free Flight is possible en route (so that each aircraft can fly its own preferred route between two en route points) but airport capacities impose “boundary conditions” on acceptance rates into terminal areas. What kinds of models would be necessary to investigate what would happen at the boundary

between airspace in which Free Flight can be accommodated and airspace in which it cannot due to capacity constraints? How can one analyze the manner in which the effects of such boundary conditions would spread/propagate through the rest of the ATM system? Finally, what are the implications for how the traffic flow management (TFM) system should be configured to operate in a way compatible with and supportive of Free Flight?

(4) Benefits and costs: Assume finally that Free Flight can still be accommodated in parts of the airspace, despite the presence of such boundary conditions and capacity limitations. What kinds of models would be needed to estimate the associated incremental costs and benefits?

A common underlying issue in the cases of (2) and (3) is that the necessary models should also be capable of providing measures of robustness (e.g., what is the range and probability distribution of the number of conflicts? what is the susceptibility to various types of uncertainty of the transitioning from Free Flight to terminal area flight? etc.).

The principal findings on each of the items (1) - (4) above are now outlined.

## 2. Models for Generating Optimal Trajectories

The Free Flight Environment assumes that user-preferred flight plans would be used by airlines and pilots whenever possible, and that these flight plans could be amended in flight. To simulate a Free Flight environment in a realistic manner, it will be necessary to generate simulated airline flight plans which are reasonably representative of the optimized flight plans which are likely to be actually flown by airlines. Flight plan optimization requires a set of realistic objectives and constraints, as well as high-performance optimization algorithms. The optimization environment is summarized in Figure 1.

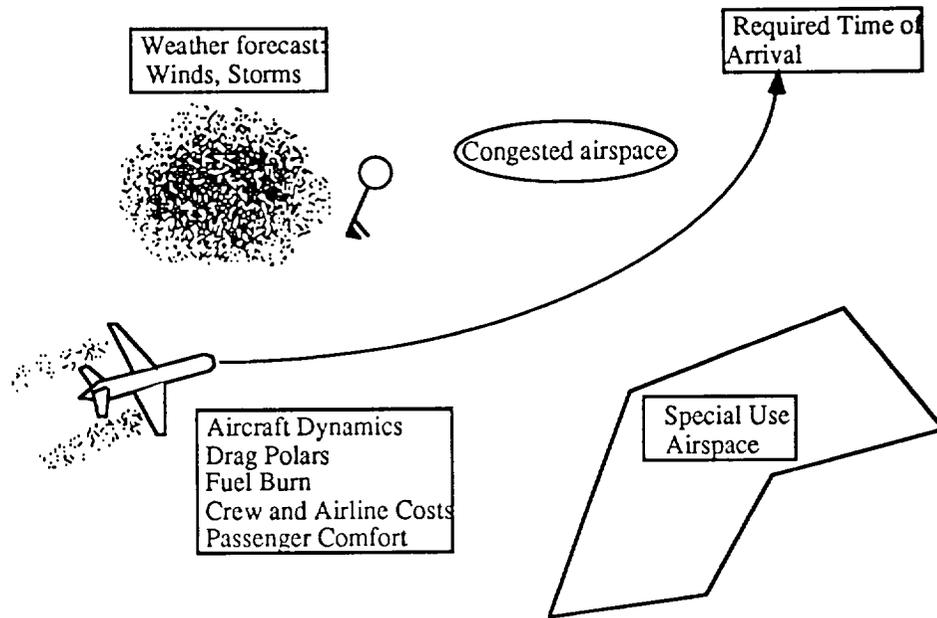


Figure 1: User-preferred flight plan optimization environment

The corresponding modeling needs can be identified by a detailed functional analysis of the flight plan optimization process in an airline setup. In the case of general aviation, most of the tasks which will be described are performed by the pilots.

### Functional analysis of optimal flight plan generation

The following functional analysis is an extrapolation from current airline practice. It outlines what an optimization process is likely to look like under certain assumptions.

The optimal flight plan generation process can be divided into two subprocesses:

- strategic flight planning
- tactical flight plan amendments

The strategic plan attempts to optimize over the entire flight while the tactical plan responds to short-term unanticipated changes in the aircraft's situation.

### Strategic flight planning

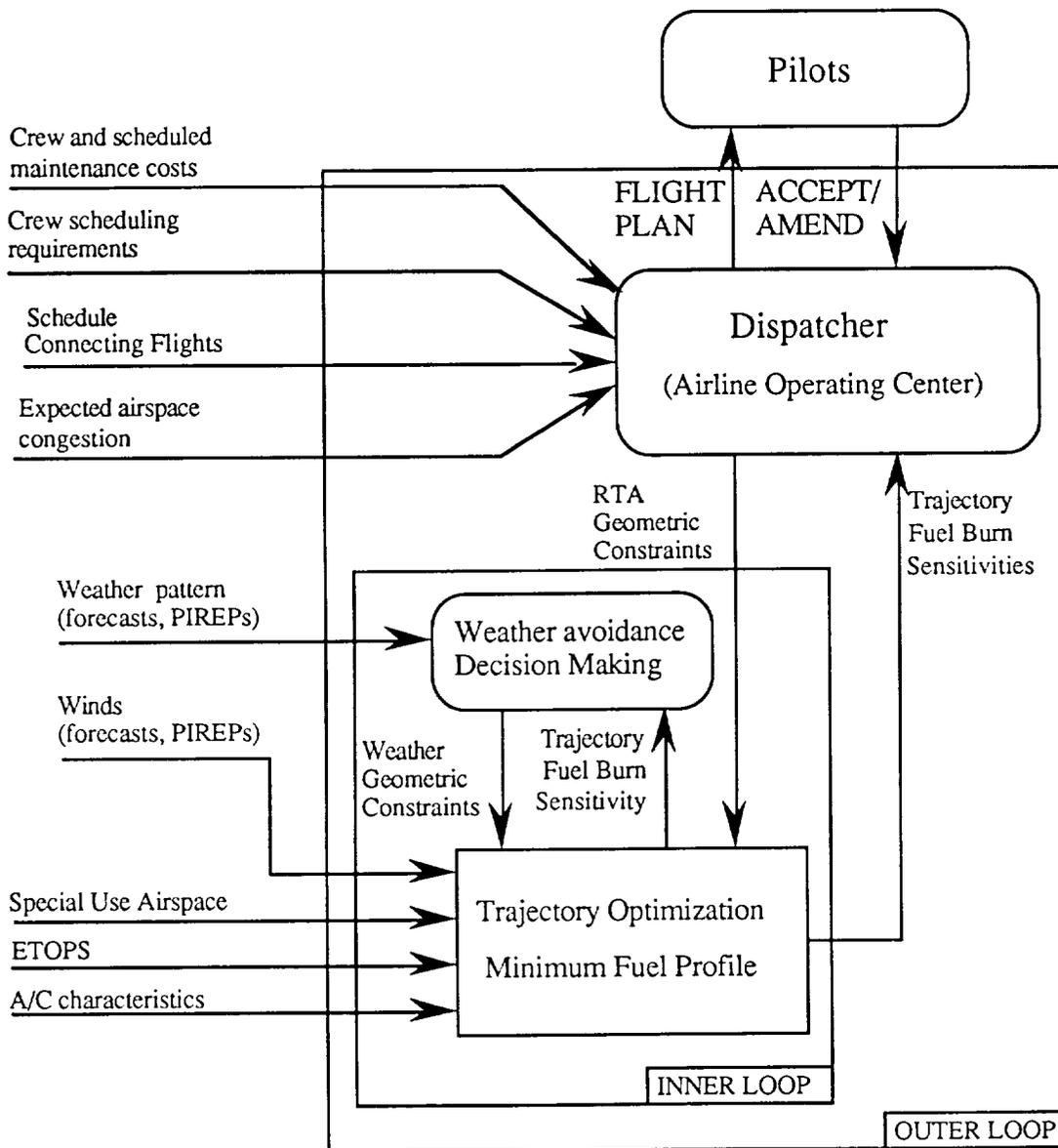
The strategic planning subprocess is presented in Figure 2. It is centered on the Airline Operating Center (AOC) dispatcher. It may run several times during a flight as new information becomes available.

The subprocess is divided into an inner loop and an outer loop. The inner loop is essentially concerned with ensuring flight safety and passenger comfort. A weather specialist translates weather forecasts and pilot reports (PIREPs) into geometric 4D path constraints and runs the Trajectory Optimization algorithm. This algorithm computes the minimum fuel trajectory, taking into account these geometric constraints and the following parameters:

- the aircraft characteristics: drag polar, engine thrust, fuel capacity and fuel consumption tables for the given payload;
- the aircraft ETOPS certification;
- the constraints defined by the dispatcher who requested the computation:
  - lower and upper bounds for the Required Time of Arrival or RTA (at a fix or at the destination airport);
  - 4D geometric constraints to avoid congested airspace which could cause delays.
- the status or level of activity of the Special Use Airspace (SUA);
- the forecast winds;
- the aircraft's current state (position, velocity, etc.).

Note that the first two remain constant during a given flight, whereas the others are updated during the flight.

The optimization algorithm also provides the fuel burn for the computed trajectory, and its sensitivity to the geometric constraints. Thus the weather specialist can get an indication of the impact of the geometric constraints he or she defined on the fuel burn of the flight, and modify them if appropriate. Once a route is chosen, the inner loop sends to the dispatcher



Note: rounded boxes involve human decision taking

Figure 2: Flight plan optimization: Strategic Level.

the trajectory, the corresponding fuel burn and the sensitivity of this fuel burn to the above parameters.

The objective of the outer loop is to minimize the total cost associated with the flight. The dispatcher takes into account airline parameters such as:

- crew scheduling requirements;
- crew and scheduled maintenance costs per hour of flight;

- fuel price;
- published airline schedules;
- expected delays at the destination airport;
- gate availability at the destination airport;
- connecting flights;

Note that the first three remain constant during a given flight, whereas the four others should be updated in flight. The dispatcher also defines 4D path constraints to avoid congested airspace which could cause delays. Then the inner loop is called to check the minimum fuel burn (and its sensitivities) for a given RTA interval. The dispatcher combines this information with the parameters listed above to choose the best RTA interval. The resulting flight plan is sent to the pilots via datalink. The pilots may accept the flight plan or request amendments. As new information on weather, winds, SUA status, etc. becomes available, the dispatcher runs the subprocess again to compute an updated flight plan which initiates at the current state of the aircraft.

#### Tactical amendments

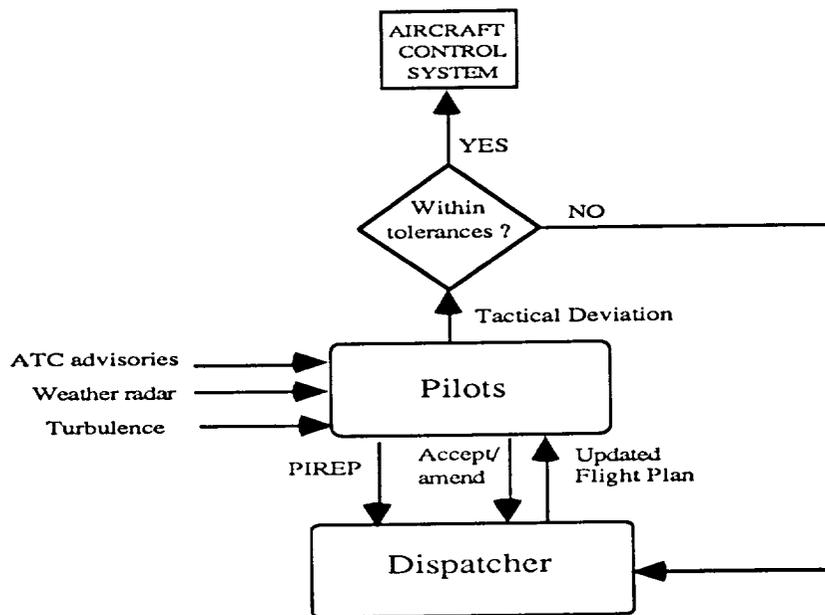
The tactical flight plan amendment subprocess is presented in Figure 3. It is centered on the pilots and is continually running during the flight.

The flight crew is ultimately responsible for the safety of the flight. They receive Air Traffic Control (ATC) advisories and data from the on-board weather radar, and may encounter unreported turbulence.

If they decide to deviate from the current flight plan, the size of the desired deviation is compared with some predefined 4D tactical limits.

- if these limits are not exceeded, the pilots may proceed with the deviation without notifying the AOC, and then go back to the current flight plan as soon as possible.
- if these limits are exceeded, the pilots report their intention to the AOC and ask for a revised flight plan.

Thus the tactical limits may be seen as a 4D corridor around the current flight plan trajectory in which the pilots may maneuver the aircraft without notifying the AOC. In any case, the pilots send to the AOC reports on the turbulence they encountered or the weather pattern they decided to avoid.



**Figure 3 :** Flight plan optimization: tactical level

## Requirements for Models

The functional diagrams in the preceding section serve to identify the models which would be needed to simulate the flight plan optimization process. In many instances models already exist and can be used with little or no modification. In other instances new models will be required.

### Existing data and models

The following data and algorithms are readily accessible and could be adapted with limited effort:

#### Aircraft characteristics

Aircraft performance data are readily available from either aircraft manufacturer manuals or from databases accumulated by the airlines during actual operations. The effort to adapt the data for use in the present context should be minimal.

### Scheduled maintenance costs and crew costs per flight hour

Sufficiently accurate estimates of these costs should be available from airline databases.

### Minimum fuel optimization algorithm

Numerous optimization algorithms (e.g., gradient methods) are currently in use and available for this need. These could be enhanced by combining them with stochastic schemes. A key element here will be to obtain efficient algorithms of varying degrees of specificity so that the model can be chosen to fit the need and excessive time and costs are not incurred.

Models and algorithms still to be developed

Models of human decision making will be needed to simulate the functions which will either be performed entirely by humans or will be only partially automated. As can be seen on the functional diagrams, these functions are:

### RTA selection

A complex model is likely to be needed to appropriately replicate the complexity of airline scheduling and connecting flight constraints. A pragmatic approach would be to model RTA selection by a simple optimization based on readily accessible parameters and constraints such as:

- approximate crew and maintenance costs per hour of flight;
- fuel price;
- number of gates at each airport;
- published airline schedule.
- minimum fuel burn for each RTA, as computed by the trajectory optimization algorithm.

At that level of approximation, delays and missed connections could be assigned an arbitrary penalty.

### Weather-related decision making

Currently, weather information and forecasts are given as text or maps obtained from various sources in various formats (surface reports, terminal area forecasts, SIGMETs, weather radar maps...). The weather specialists (or the general aviation pilots) integrate all this information and define constraints on the flight plan. This process involves experience and risk-taking. These knowledge-based decisions would have to be generated in the simulation.

### Tactical weather avoidance maneuvers

A model would be needed to simulate the behavior of pilots who encounter unexpected weather patterns or turbulence. This model could be based on empirical rules obtained from airline pilots.

### ATC advisories

Models simulating the resolution of ATC conflicts are also required; these will be considered in the next section of this document.

Other models that will be needed include:

### Simulated weather/wind generation

Weather and wind generation models would have to be developed for the simulation. They could be based on statistical data, wind and weather models currently used to produce forecasts, or simplified climate dynamics. In addition, this model would also generate corresponding weather forecasts to be used by the weather-related decision making model. These forecasts should include a realistic amount of uncertainty.

### Data availability and accuracy

Airline Operation Centers do not always have the most current or accurate information, in particular regarding current SUA status and expected delays at the destination airport. To reflect this fact in the simulation, the data made available to the dispatcher should be a delayed and/or altered account of the real situation. These delays and alterations would have to be modeled.

## **3. Conflict Models**

Given that more than one aircraft may be flying in local airspace, conflicts between aircraft may occur that necessitate replanning or maneuvering to maintain separation. The frequency of conflicts and their effects on aircraft must be examined because conflicts may impact the safety and efficiency of traffic flow. These analyses will require modeling and simulation tools which can be organized into several categories:

(1) The density (spatial or temporal) of conflicts will be of interest as a predictor of the amount of additional intervention that will be required to maintain aircraft separation. Models of the traffic flow are needed to determine the frequency and form of conflicts (e.g., the geometry and number of aircraft involved in a conflict).

(2) Conflict probe algorithms must be developed to alert controllers and/or pilots that a conflict exists. These probes will use sensor and datalinked information such as aircraft position and intended path to determine if intervention is required. Models are needed here to determine the effectiveness (e.g., false alarm rate) of conflict probe methods.

(3) Once a conflict is detected, some method of resolving the conflict is needed. Models are required to determine whether proposed resolution methods are effective in maintaining separation and to determine the impact of the conflict on the overall traffic flow. Additionally, human performance considerations during conflict resolution need to be modeled.

These three categories of conflict models are shown in Figure 4. First, aircraft trajectories must be generated based on a model of assumed parameters such as aircraft type, routing logic, etc. A conflict detection model then determines which of these trajectories result in conflicts. A model for conflict resolution is also needed to obtain performance metrics such as accident rate based on some conflict resolution system.

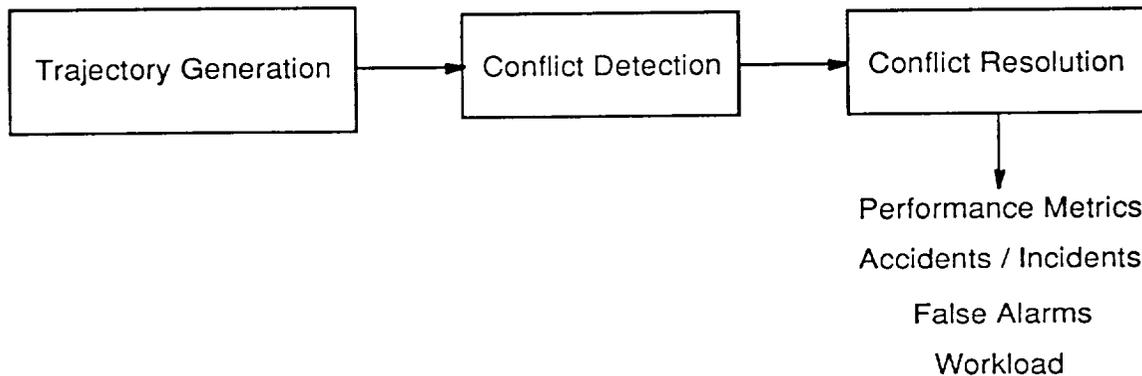


Figure 4: Basic Model Requirements

A particular analysis may only consider the behavior of an ATM system within a single model category or between sets of models. For example, one model currently under development, is used primarily to generate aircraft trajectories [Roberts, et al. 1994]. Other models take aircraft trajectories as inputs, detect where conflicts may occur, and provide as an output suggested avoidance maneuver options to the controller [Medioni, 1994; Eby, 1994]. A brief description of the types of models that form the model categories in Figure 4 is now provided.

## Trajectory Generation Models

At the top level, models are needed to define the spatial and temporal distributions of aircraft trajectories. Trajectory Generation Models must cover several areas:

(1) **Airspace models.** Models that define differences between the overall route structure or route generation methods in different regions are needed for the analysis of free flight on a large scale. For example, aircraft routings may be determined differently in transoceanic regions than over continental regions. Similarly, limitations in navigational facilities may result in a case where free flight may be possible in one region but not possible in another. Airspace models define the extent to which free flight is possible in different regions (Figure 5).

(2) **Aircraft route generation models.** Under the current ATC system, routes are typically based on established airways and separation requirements. The Free Flight concept would use a route structure in which each aircraft plans and modifies its route with limited ground intervention as described in Section 2 above. Some aircraft routes may be developed to optimize fuel flow, while others may be centered on achieving a desired arrival time. Generally, a different set of route generation models would be developed for each region defined by an airspace model from area 1 above.

(3) **Local or tactical models of aircraft trajectories.** It may be desirable to concentrate on the traffic in a local region where two or more aircraft must modify their routes to avoid collision or severe weather. Thus, local movement models will be needed to analyze the traffic flow within a defined region.

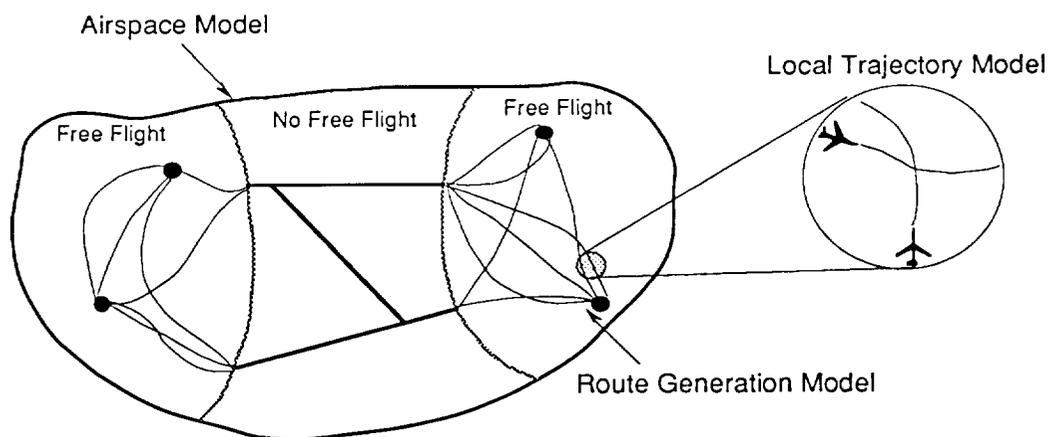


Figure 5: Trajectory Generation Models

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## Conflict Detection Models

A second set of models is focused on estimating the rate or density of conflicts. Based on the routes obtained from a Trajectory Generation Model, a Conflict Detection Model is used to determine where and when conflicts may occur. Also, a Conflict Detection Model could provide measures of the geometry and number of aircraft involved in a particular

conflict. Several initial concepts for conflict detection for free flight have been suggested [RTCA, 1995; Winer, 1995].

An important part of Conflict Detection is the prediction of where the aircraft will be in the future. This prediction can be a simple extrapolation based on the current position and velocity vector of the aircraft or can include information relating to the intended trajectory of the aircraft. For example, knowledge that an aircraft will level off at some altitude can be used to inhibit a conflict alert that would otherwise be issued based on a continued projection at the current descent rate.

The aircraft's position in the future generally becomes more uncertain as the extrapolation continues. Thus, even though a conflict is projected to occur in the future, it may be the case that the probability of a conflict is small. The ability to accurately predict the future trajectory is a key issue. Any conflict detection method must balance alerting too early and having false alarms against alerting too late and not providing enough time or space to avoid an incident. By providing additional state measurements or by improving sensor accuracy, it is possible to improve performance. Models will be required in this area to design and evaluate conflict detection concepts to determine whether there will be an excessive rate of false alarms or missed detections. An example study of the methods that will be needed to develop these models can be found in [Kuchar & Hansman, 1995].

Because the severity of a conflict is a function of the ability to resolve the conflict, Conflict Detection Models will most likely also require data from a Conflict Resolution Model to define what situations are sufficiently hazardous to be termed conflicts.

## Conflict Resolution Models

When aircraft trajectories can be estimated accurately well into the future, the interactions between aircraft can be strategic, involving negotiation and flight plan changes conducted directly between aircraft or through a ground control station. If it becomes clear that a collision is imminent, tactical interactions will be required, involving immediate small-scale maneuvering to avoid an accident. Aircraft involved in such a tactical interaction would then return to their strategic routings after resolving the incident.

A set of models is required to analyze the interactions between aircraft when a conflict occurs. As shown in Figure 6, this set includes Dynamics, Collision, State Estimation, Alerting, Resolution Selection, and Response models. These models will be required for both strategic and tactical conflict situations. Example models have been developed for the evaluation of the Traffic Alert and Collision Avoidance System (TCAS) [Burgess, 1993] and for closely-spaced parallel approach [Shank & Hollister, 1992].

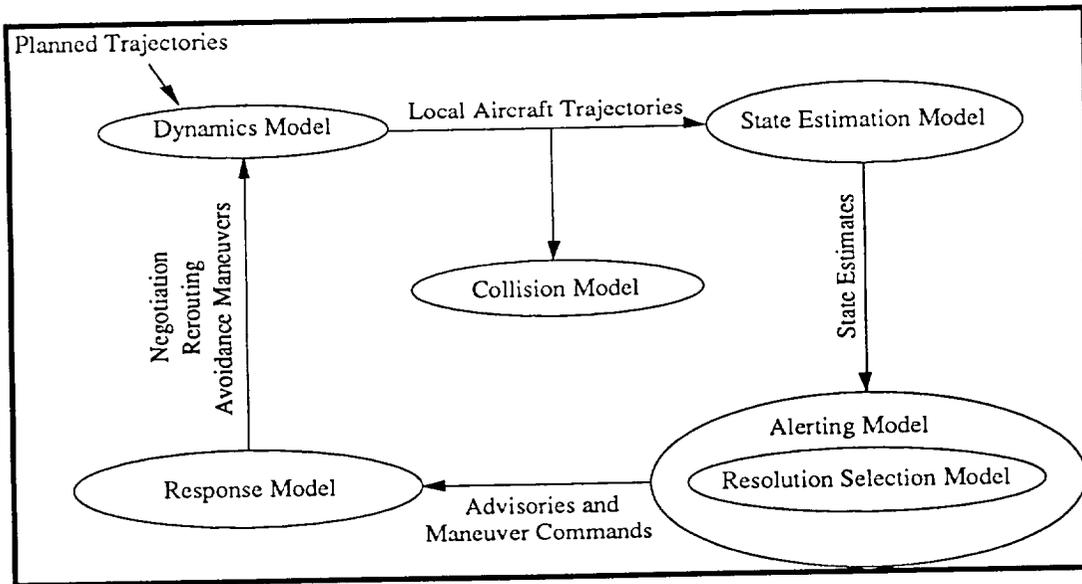


Figure 6: Conflict Resolution Submodels

(1) Dynamics. The dynamics of the aircraft involved in a conflict must be modeled. Models of aircraft type, cockpit control and display methods, and human performance are included here.

(2) Collision. A Collision Model is required to determine when collisions occur and provides a measure of the effectiveness of the conflict resolution system. This model includes the criteria that define a collision (e.g., less than 500 ft slant range). In some applications it may be of interest to analyze the amount of near miss events, in which case the Collision Model can be modified to define the event of interest (e.g., less than 1000 ft slant range).

(3) State Estimation. The states of the aircraft are estimated by each aircraft and/or by a ground control station in some manner, including the use of sensors and information transmitted between aircraft or between aircraft and the ground. A Sensor Model describes the ability of a conflict detection or resolution system to monitor each aircraft. This model should describe the state variables that are available and the uncertainties present in the state estimates.

(4) Alerting. The state estimates are available directly to the pilot or controller and/or to an automated alerting or advisory system. An Alerting Model describes the mapping from state estimates to the decision that action is needed. This decision is based on the available information and may be performed by an automatic alerting system or by a pilot or controller.

(5) Resolution Selection. Within the Alerting Model, a Resolution Selection Model is used to determine what course of action should be taken to avoid an accident. Example resolutions include negotiation with other aircraft or ATC for strategic rerouting, or tactical, immediate avoidance

maneuvers. Several stages of action are also possible, including cautions (e.g., “traffic”), restrictive warnings (e.g., “don’t turn left”), and executive warnings (e.g., “turn left”).

(6) Response. A Response Model describes the actions that each pilot takes in response to the alerts or other state information regarding other aircraft or weather. This model includes human performance parameters such as response time, and the complexity and aggressiveness of the maneuver that is actually performed. Actions taken by aircraft then are passed to the Dynamics Model, which returns updated trajectory information as the loop repeats.

## Interactions Between Models

The Conflict Resolution, Conflict Detection, and Trajectory Generation Models are linked together. These connections allow for the consideration of multiple aircraft involved in replanning or avoidance actions. The evaluation of an ATM concept will require the consideration of incidents involving several aircraft at once. A resolution system designed to protect against a single proximate aircraft may be inadequate to protect against two or more threats. Also, the dynamics of the responses to traffic may have repercussions on the routings of aircraft in the local area. Aircraft that are not immediately affected by an encounter situation may be indirectly affected as the proximate traffic maneuvers. In some situations, instabilities in local traffic flow may occur as multiple aircraft respond to multiple threats.

Additional, human-centered models will be required to produce performance metrics such as pilot or controller workload and capacity to respond to alerts as desired. These models must consider the interactions between the human operator and the display of conflict information and the procedures used to resolve the conflicts (one possible candidate is MIDAS [Corker & Pisanich, 1995]).

### Robustness

As discussed earlier, evaluation of robustness measures will be an important function for the conflict models described above. Efficient methods for evaluating robustness are likely to include both simulations and statistical parameter evaluation methods. Inevitably robustness measures must account for and quantify uncertainty. Evaluating the relevant statistical measures (e.g., the probability distribution for the number of conflicts over some period of time) can sometimes be accomplished by repetitive running of simulation models over randomized conditions (i.e., Monte Carlo methods). Alternatively, there are often situations where the most effective approach is a direct propagation of statistical measures such as probability densities or moments. Efficient conflict models are essential in both instances.

For the level of complexity inherent in the Free Flight concept, past experience has shown that neither the Monte Carlo nor the statistical propagation approach alone is likely to be sufficient. Often the most effective method is to combine the two approaches. In some instances

Monte Carlo simulations at the micro level can efficiently determine the necessary input quantities for the macro analysis of a desired global statistic through propagation. For this type of evaluation the mathematical models serve as the simulation medium for the Monte Carlo analysis and they provide the relationships and parameter values for statistical propagation. In other instances the reverse procedure is most efficient and a statistical evaluation at the micro level creates parameters for randomization of a simulation model at the macro level. Once again the mathematical models play their appropriate roles but now in reverse order. Experience has shown that combinations of the two approaches can provide both the flexibility and effectiveness necessary to answer relevant questions in quantitative fashion.

#### 4. Modeling Interactions with TFM

We now turn to models that would help investigate how Free Flight can work in the presence of some of the severe capacity limitations that exist in major terminal areas and under less than ideal weather conditions. Closely related to this is the general problem of how the traffic flow management (TFM) system would be operated in a way most compatible with Free Flight.

Because these questions are so critical, it would seem that a two-level modeling approach, one with an emphasis on *strategic* issues and the other on *tactical* ones, might be required. The strategic model would adopt a *macroscopic* viewpoint and concentrate on developing approximate representations of overall traffic patterns under various levels of TFM decentralization in the presence of Free Flight. This strategic model would necessarily be of a *regional or national* scope, encompassing a number of airports and en route centers. By contrast, the tactical model would be *microscopic* in nature, would look into the detailed behavior of individual aircraft, once airborne, and would place its emphasis on a detailed examination of the transition from airspace in which Free Flight can be accommodated to airspace where it cannot, due to capacity limitations. The scope of this tactical model could be limited to a *single major terminal area* of sufficient complexity, e.g., Chicago.

#### **The Strategic Model**

The strategic model would create an environment ("testbed") in which: (1) the behavior and strategies of ATM system users (airlines and general aviation) and TFM operator (the FAA's central, regional and local units) could be represented under *a variety of alternative TFM approaches*; and (ii) the consequences of this behavior and strategies could be explored approximately by identifying where the major concentrations of traffic would take place and the resulting delays and costs to individual users and/or classes of users. Table 1, based on ongoing research at Draper Laboratory and MIT indicates some of the types of alternative TFM approaches that need to be investigated. An implicit assumption in Table 1 is that, in the "Free Flight era", TFM will rely primarily on the "required time of arrival" (RTA) method outlined in Section 1 and that specification of a "controlled time of departure" (ECDT) from the airport of origin will not be necessary. (Whether ECDTs will indeed prove unnecessary is, in fact,

one of the many open questions that would have to be investigated with the models described here.)

Table 1 suggests the kinds of modeling capabilities that the strategic model should have. For example, under one alternative which is not much different conceptually from the existing system (see "Centralized" row in Table 1), the FAA-operated TFM would be the sole determinant of (dynamic) arrival slot assignments, whenever weather conditions would dictate the initiation of a gate-holding "program" for a particular destination airport. The TFM system would specify the slot assignment of every individual flight and would provide to each flight a required time of arrival (RTA) at some location in the terminal area of destination or at some distance from it. (This RTA would, of course, be consistent with the corresponding slot assignment.)

The airlines and the other users would then be confined to following these TFM mandates, with each airline's only alternative option being to cancel one or more of its flights and utilize the emptied slot(s) for other flights of its own -- flights that would, otherwise, have arrived at the congested airport at a later time. Under such an approach to TFM, Free Flight would be practiced by airlines (and possibly other airspace users) only to the extent of developing and implementing flight plans and trajectories that would be consistent with the RTAs assigned to each flight, i.e., that would deliver the corresponding aircraft at the specified location at the specified time.

The strategic model must then be capable of simulating how airlines would behave in such an environment. For instance, for each given flight, an airline would have to determine the "optimal" (from its point of view) trade-off between how much delay would be taken on the ground ("gate holding") and how much on the air in order to meet the flight's RTA. The model would also require a capability to examine what would happen in the entire ATM system (delays, queue lengths, fuel consumption, etc.) after each airline had made its decisions about the (4-D) trajectory of each one of its flights.

Even more advanced capabilities would be required of the strategic model to investigate more "decentralized" future TFM environments. Consider, for example a partially decentralized TFM system (Table 1, "Partially Decentralized I"). Here, the role of the TFM system's operator would be more limited: the FAA would only assign sets of slots to each airline for each congested airport over specified periods of time and would leave it entirely up to each airline to decide how it would utilize its own set of slots in each period. (For instance, UA might receive from the FAA 6 of 17 available landing slots during the 9:00 to 9:15 time period at ORD of a morning when the arrival acceptance rate at ORD is limited to approximately 70 per hour, instead of the more typical 100; these 6 slots might be allocated to UA to reflect UA's fraction of total arrivals originally scheduled for ORD for between 9:00 and 9:15 that morning.) This means that the airline behavior that would have to be simulated extends beyond developing flight plans for individual flights that complied with specified RTAs, as required under the "centralized" TFM alternative. Now, it is also necessary to model how each airline would allocate its available set of slots among those of its flights which can utilize these slots. Such a process would have to take into

consideration airline “bank” scheduling, flight connections, crew connections, etc. It may be extremely difficult to develop such models. In addition, the strategic model will need a broader range of capabilities in exhibiting aggregate system characteristics since slots, under this partially decentralized system would specified in terms of sets over extended time intervals (e.g., over 15-minute periods) as opposed to distinct RTAs for individual flights.

## **The Tactical Model**

As noted above, the tactical model would include a considerably higher level of detail than the strategic one but would be of significantly more limited scope. It would essentially consist of a detailed model of a terminal area with one or more busy airports plus the surrounding en route and transitional airspace. The tactical model would emphasize those aspects of ATM which are particularly relevant to the dynamic flow management functions. Dynamic forecasts of winds and of airport acceptance rates, as well as descriptions of the characteristics of the arrival streams and of the topology of the terminal area should be features of the model. Most important, the model must also include an implementation of the dynamic flow management algorithms utilized by TFM. For instance, it should be able to capture the effects of a CTAS-like terminal-area automation system, as well as of any other techniques used to meter traffic past arrival fixes, effect high- and low-altitude holding, exercise vectoring and speed control, etc.

### Stochastic Aspects

Central to both the strategic and the tactical models outlined above would be a capability to simulate stochastic phenomena. This is because it will be necessary to ascertain the robustness of alternative TFM arrangements under Free Flight in the presence of uncertainty due to: the variability of airport weather; the consequent probabilistic variations in airport acceptance rates; uncertainties about the true airport demand on any given day; deviations of actual arrival times at specific waypoints from the specified RTAs at these waypoints; etc.

## **5. Evaluating Costs and Benefits**

In evaluating any new ATM system concept, it is desirable to balance the costs of its implementation and operation against the benefits it achieves. There is also the aspect of the timing of costs and benefits since costs are likely to be paid initially, while benefits are typically received over the long term. This calls for the use of appropriate discounting practices that render “commensurable” dollars expended or received at different times. Additionally, the development of credible time estimates of benefits and costs requires forecasts of future ATM system activity levels.

There are three categories of participants in ATM who can receive significant benefits from innovative ATM concepts:

- a) Aircraft Operators (Airlines, General Aviation, Military)

b) Airline Passengers/Shippers

c) ATM Service Provider

Each may receive different types of benefits and it is necessary to be careful not to double or triple count the same benefit. For example savings in operating the ATM system can be passed on to aircraft operators in the form of reduced ATM user fees, which can then be passed on to passengers in the form of reduced fares. A correct accounting would book this benefit only once, but the evaluation should also indicate that three constituencies are affected.

**Table 1: Alternatives for Traffic Flow Management (TFM) with Free Flight**

	<b>Initial allocation of arrival slots (1)</b>	<b>Final assignment of arrival slots to individual flights (2)</b>	<b>Planning and revisions of flight trajectories (3)</b>
<b>Centralized</b>	TFM system operator (FAA) allocates arrival slots to individual flights	TFM system operator (FAA) assigns slots (see Column 1); each airline may cancel and substitute flights	Airlines (and other airspace users); TFM system operator monitors for feasibility, conflicts.
<b>Partially Centralized</b>	TFM system operator (FAA) allocates arrival slots to individual flights	Each airline suggests alternative assignment of the slots allocated to its (for its own flights only; TFM system operator approves or rejects.	Airlines (and other airspace users); TFM system operator monitors for feasibility, conflicts.
<b>Partially Decentralized I</b>	TFM system operator (FAA) allocates sets of arrival slots to individual airlines over time intervals of some duration (e.g., 15 minutes)	Individual airlines allocate their own sets of slots among their own flights.	Airlines (and other airspace users); TFM system operator monitors for feasibility, conflicts.

<b>Partially Decentralized II</b>	TFM system operator (FAA) allocates sets of arrival slots to individual airlines over time intervals of some duration (e.g., 15 minutes)	Airlines may trade slots among themselves. Then each individual airline allocates its own set of slots among its own flights.	Airlines (and other airspace users); TFM system operator monitors for feasibility, conflicts.
<b>Decentralized</b>	TFM system operator (FAA) simply informs airlines about anticipated availability of capacities at potentially congested airports.	Airlines decide what they will do. They may trade slots, cancel or delay flights, follow the original schedule, etc.	Airlines (and other airspace users); TFM system operator monitors for feasibility, conflicts.

**Table 1 (continued): Alternatives for Traffic Flow Management (TFM) with Free Flight**

The current Free Flight system envisages a major change in the way we do Traffic Flow Management for flights into the major hub airports. There would be considerable benefit in increasing landing capacities, but absent such an increase, any benefit in this area must presume that the current set of seven methods for executing TFM in the USA is inefficient; and that the new TFM method under Free Flight will eliminate these inefficiencies. This requires a definition of exactly how the old and the new TFM methods work, models to evaluate performance and studies to document the current TFM problems at major hubs.

Similarly, the current Free Flight system envisages an adaptive sectorization whereby sector sizes and manning can be quickly redefined to allow a re-routing of enroute flows around weather, etc. without overloading current sectors. There is a current re-routing tool which has not achieved operational status which has the potential to equitably re-route traffic subject to current sector workload limits. This new tool should be studied to see if the inherent problems in training controllers to work in an adaptive sectorization mode are worthwhile.

The Free Flight ATM concept will evolve, with both new and modified versions appearing in the future. Each new concept is likely to require operational models to evaluate its performance in one or more dimensions. There is a battery of operational models which will be needed as well as forecasts of traffic activities and operational costs - for airlines, for GA, and for military users; and for specific airspace domains, US enroute, Oceanic, Major hub airports, etc.

There are many aspects of both costs and benefits which must be systematically accounted for. A new or modified ATM system is likely to involve investments in both ground based and airborne equipment. Typically, ground based equipment costs will be borne by the ATM system providers while airborne costs must be absorbed by aircraft operators. In corresponding fashion other costs such as personnel training, system maintenance, software costs etc. will accrue to ATM providers or aircraft operators.

The benefit most likely to accrue from a new ATM system is time savings which will result from increased capacity of the ATM system. For air trips between certain terminals, in today's ATM system, there are built in time delays due to capacity constraints at peak traffic times. In this context time delay is defined as the excess time to accomplish a trip, over the trip time for a traffic-free flight, as defined earlier. Increasing the capacity of the ATM system should allow a direct decrease in the aggregate delays currently imbedded in nominal schedules as a result of capacity constraints at peak traffic times. For aircraft operators time savings translate into reduced fuel and marginal aircraft operating costs, reduced interrupted trip expenses, and reduced costs for irregular operations. For passengers the time savings should be translatable into equivalent cost savings. For business travel it is likely that this time to cost benefit translation can be accomplished rather directly though personnel costing. For personal and pleasure travelers the translation is more subjective and may require some form of rationalization to relate time delays to equivalent costs.

In order to correctly evaluate costs for any new ATM system concept, models of cost and benefit will be required. In the following sections some of the required cost/benefit aspects of these modes will be discussed.

ATM Provider Cost Models-The costs which must be borne by the ATM provider are likely to constitute a major portion of the total expense incurred using any new ATM concept. Non-recurring costs will accrue for capital equipment expenses for the initial development and construction of facilities as well as the initial training expenses necessary to implement the concept. Recurring costs will accrue for operations and maintenance personnel, replacement equipment, and continual training of personnel to maintain proficiency. For any particular ATM concept models of these costs will be necessary to allow the evaluation of costs incurred in relation to the benefits that may accrue as a result of implementing the concept. These models should allow the incorporation of projected growth of traffic and the associated required upgrading of the system as a function of time. As discussed above, the cost aspects of traffic flow management and adaptive sectorization must be included if Free Flight is to be effectively evaluated. An area of particular importance will be costs and potential savings that may accrue due to automation. Models must be capable of quantifying the tradeoffs between automation and manual operation of various elements of any ATM concept.

Aircraft Operator Cost Models-The operators of aircraft (Airlines, Military, GA) are likely to be the major beneficiaries of any new ATM concept and cost models of these constituencies will be necessary to quantify projections of these benefits. Models for airline personnel costs and marginal aircraft operating costs are the most readily available of these three categories. These cost models must facilitate the evaluation of airline operator cost savings resulting from reductions in delays attributable to ATM capacity increases. Models for military and GA costs/benefits will be more difficult to realize and are likely to be more subjective in nature. Additionally, all models must quantify the capital expense of new airborne and ground based equipment required to allow aircraft operation in any new ATM system, as well as recurring costs for maintenance and personnel training.

Airline Passenger/Shipper Cost Models-As discussed earlier it should be possible to create cost models for business travelers directly from personnel costs attributable to delays. Similarly, cost models for shippers should reflect the marginal costs for shipping that accrue as a result of delivery guarantee costs and/or personnel expenses which result from delayed shipments. In addition some means of quantifying equivalent costs for personal and pleasure travel must also be determined. These costs are far more subjective in nature and not as readily and objectively defined as for business travelers and shippers. Models which facilitate parametric studies over ranges of possible values may be the most useful approach for these classes of travelers.

Common Requirements for Cost Models-All of the cost models should be capable of and/or be adaptable to both deterministic and probabilistic studies. In many instances there will be a need for a direct evaluation of costs based on a specific set of parameters. For example, an aircraft operator model should be capable of determining the change in marginal

costs for a given airline which results from an ATM capacity increase for a specific trip between two cities. In addition, the aircraft operator model must also be capable of adaptation to and/or integration with other models to obtain statistical estimates of relevant cost statistics. An example here might be the determination of the expectation and possibly higher order statistics (e.g. standard deviation etc.) for total dollar savings for airlines and total costs for an ATM free-flight concept. In particular, the model would incorporate uncertainties due to weather, economic forecasts over both time and geographical regions, and possibly projections of technical capabilities and costs affecting levels of automation for the ATM system concept.

ATM Capacity Integration Model-To be most useful the cost models described above must be amenable to integration with other models so that the costs and benefits of increased ATM system capacity can be evaluated. In particular, the conflict models described earlier are essential for quantifying capacity increases that may be achievable with any particular ATM concept. The cost models described in this section create the relationships between capacity increases and cost benefits to various constituencies. Similarly, both the recurring and non recurring costs to both the ATM operators and the users, would also be obtained from these models. Implicit here is the need for a simulation of an ATM concept over a desired time period, appropriately discounting costs and benefits over time. An ATM Capacity Integration Model would provide the framework for this time line simulation by facilitating the integration of the various models described earlier. This model would serve as an integration medium. It would establish the necessary initialization and information transfer facilities between models necessary for the wide range of tradeoff studies which are likely to be necessary to evolve a truly effective ATM concept. To be effective this portion of the overall modeling capability must function much like a modern computer operating system, creating appropriate user interfaces, managing resources, facilitating interchange of information and creating an appropriate environment for effective utilization of the various models and associated data bases.

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## Appendix B: Case Study on

### Airport Surface Traffic Management Automation

#### 1. Purpose

This is a report on the second case study carried out under the MIT Model Review and Evaluation project undertaken in connection with NASA's AATT Program. The purpose of this document is to identify in generic terms the modeling capabilities needed by researchers to study issues in Airport Surface Traffic Management (ASTM). It focuses on the evaluation of new technologies for Communications, Navigation, Surveillance, and Human-Centered Automation which have the potential to improve safety, reduce delays, and lessen controller workload at busy commercial airports in the US. It is desirable to evaluate these new concepts to assess their operational feasibility and their costs and benefits before embarking on a major R&D effort or implementation program. Models are needed to perform these evaluations.

Four main factors motivate ASTM. The first is the occurrence in the past few decades of several aircraft collisions on airport surfaces and many more near misses; it is hoped that the enhancements made in managing surface traffic will both reduce the number of such incidents and help in resolving those that do occur more rapidly. The second is the existence of delays in travel between the runways and the gates; better scheduling and communications may streamline this procedure. Third, the task of managing the traffic on the airport surface is currently performed solely by the controller; allowing some of this work to be performed by automated systems could improve efficiency and allow the controller more time to deal with critical events. Finally, continual growth in the volume of air traffic is exacerbating all of the aforementioned problems.

In order to illustrate the modeling capabilities needed to evaluate the impact of the planned changes to surface traffic management, this paper is broken down into three sections. The first gives general background on airport surface operations. The second details the changes to this system being considered and describes how the FAA's ASTA program would implement them. Finally, the modeling capabilities needed to evaluate surface traffic automation systems are outlined.

#### 2. Description of Operations on the Airport Surface

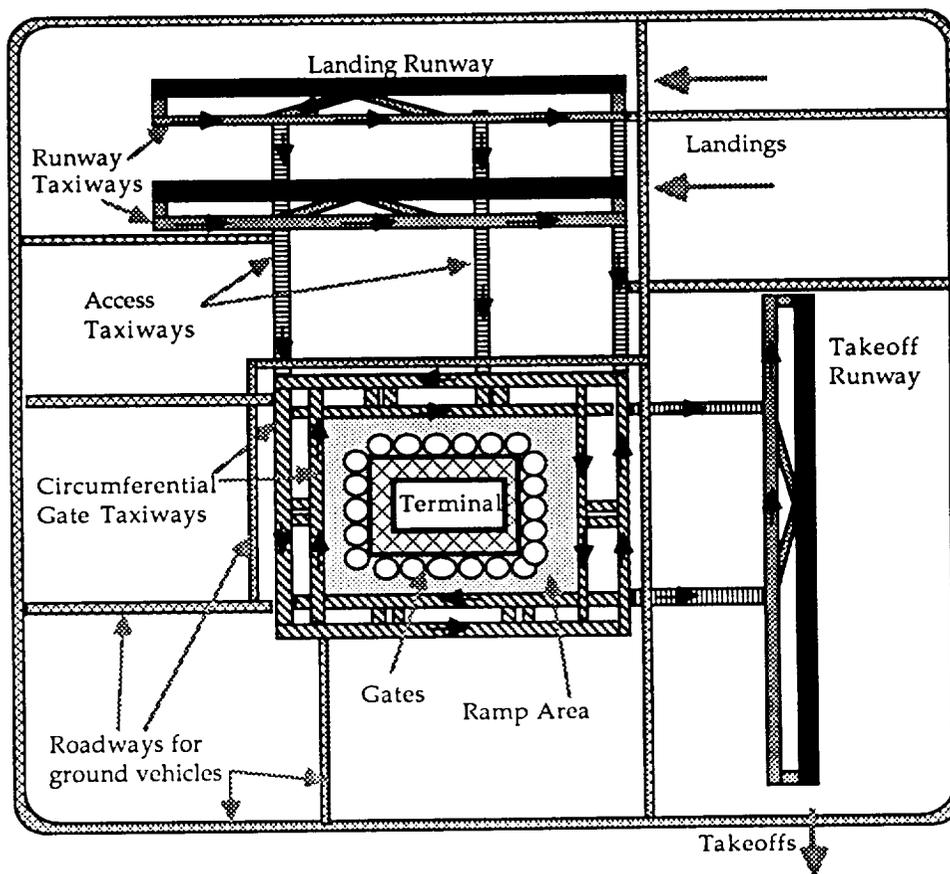
##### 2.1 - Airport Generic Layout

A schematic for a generic airport surface layout of the taxiways, roadways, and parking gates is shown in Figure 1. At a typical busy airport there are one or more runways dedicated to either landing operations, or takeoffs, or perhaps both operations. The assignment of landing or takeoff operations to the runways by type of aircraft will be called a **Runway Operating Configuration**. Every runway has a full-length parallel **Runway Taxiway** which is used for one-way traffic depending on the direction of use of the runway.

Then there are the **Access Taxiways** which are used to connect the Runway Taxiways to the ramp areas. Access taxiway segments can be used in one direction at a time depending on the Runway Operating Configuration in use. At any point in time, there is a limited set of one-way taxiway segments in use depending on the runway configuration - one set for taxi-in traffic flows, branching out from the landing runways in a tree-like structure to reach the various ramp areas; - another set for taxi-out traffic flows converging on the takeoff runways from the ramp areas in a root-like structure with a number of merge points. There are usually a number of crossing points between the tree and root structures

of the taxiways and the runways. The goal of the airport layout designer is to minimize the number of these crossings if possible.

**FIGURE 1 - GEOMETRIC ELEMENTS OF THE AIRPORT SURFACE**



The Access Taxiways connect into the **Gate Taxiways** which may consist of a pair of parallel, circumferential, one-way taxiways surrounding the gates. This pair of taxiways allows traffic flows both ways between the gates for all runway configurations; and unlike the rest of the taxiways, they normally maintain the same directionality independent of the runway configuration in use.

The schematic shown in Figure 1 is very much simplified. Every airport has its unique layout, and a unique set of surface traffic flows and problems which arise from that layout as it has developed over time. Research into operational concepts for ASTM requires that analytical and simulation models should be very adaptable to quite different airport layout configurations and allow for easy modification of the geometry and traffic procedures.

## 2.2 - Airport Surface Vehicles

There are two types of vehicles on the airport surface;

- 1) the aircraft which use the taxiway system to taxi-in and taxi-out between the runways and the ramp areas around the gates/parking positions, cargo areas, etc.;

2) the various airport and airline ground service vehicles which may use their own airfield roadways, or may be using the taxiways and runways (inspection, snow removal), and which are active in the ramp areas around and between the gates.

These vehicles move at a wide range of speeds depending on location, traffic, visibility, day/night, etc., as there are no speed limits or expected speeds on the airport surface. Aircraft cannot see behind themselves generally, and many pilots cannot see either their wingtips or their engines and may need assistance in close maneuvering in the ramp area to avoid other aircraft, buildings, or snow banks, and to avoid causing damage by jet blast.

### **2.3 - Current Airport Surface Traffic Management**

Today's concept for traffic control on the airport surface may be termed the "Free Taxi" concept. The landing and takeoff operations are controlled by the Local Control sectors in the Tower. After landing and clearing the runway at some exit selected at the pilot's discretion, Local Control will handoff the aircraft to Ground Control. The aircraft may then be asked its destination on the airport, and will be given a "Taxi Clearance" from its current location via a routing specified in terms of taxiways and intersections which have various names. Pilots are expected to provide their own Navigation, Guidance and Separation Assurance, although Ground Control may intervene from time to time to resolve meetings at a crossing or merge point, or to provide a clearance to cross a "live" runway. All vehicles which are allowed out onto the airfield and its taxiways usually must have voice radio contact with Ground Control to provide the Communication function. Aircraft ready to leave the gate will call Ground Control for "Taxi Clearance" identifying their location on the airport, and normally are assigned to a takeoff runway and receive a routing at that time.

The Navigation and Guidance functions are manual and visual. Pilots and drivers need reasonable visibility to proceed, and are assisted by taxiway edge lighting, perhaps taxiway centerline lighting, and more recently, a standard set of large, lighted signs to identify the intersections, runways, and taxiway segments.

The Surveillance function (needed in the Tower(s) and each aircraft and vehicle) is also manual and visual, although there are some very primitive systems of surface surveillance using radar. There are many instances today where the visibility from the Tower is not sufficient for the Ground Controller to see the traffic on certain parts of the airport, and at night it is difficult to maintain identity of a set of navigation lights (or yellow caution lights on ground vehicles) as they move around the taxiway network.

In the principal ramp areas, there may be several independent Ramp Traffic Control sectors for aircraft and various ground vehicles. Such Ramp Traffic Control may be provided by each airline at a US airport to establish the sequence of gate arrival and departure operations (gate assignment, gate arrival guidance, unloading, refueling catering, cleaning, loading, pushback, snow and ice removal, etc.). Most of the ground handling vehicles on the ramp do not have radios and are individually responsible for their routings and separation assurance (there usually is some traffic training required to qualify to drive ramp vehicles). These Ramp Traffic Control sectors receive advisories on gate holds desired for ATC Congestion Management directly from the Ground Traffic Control sector; and conversely, advise Ground Control whenever the gates are full and cannot accept any more arriving aircraft.

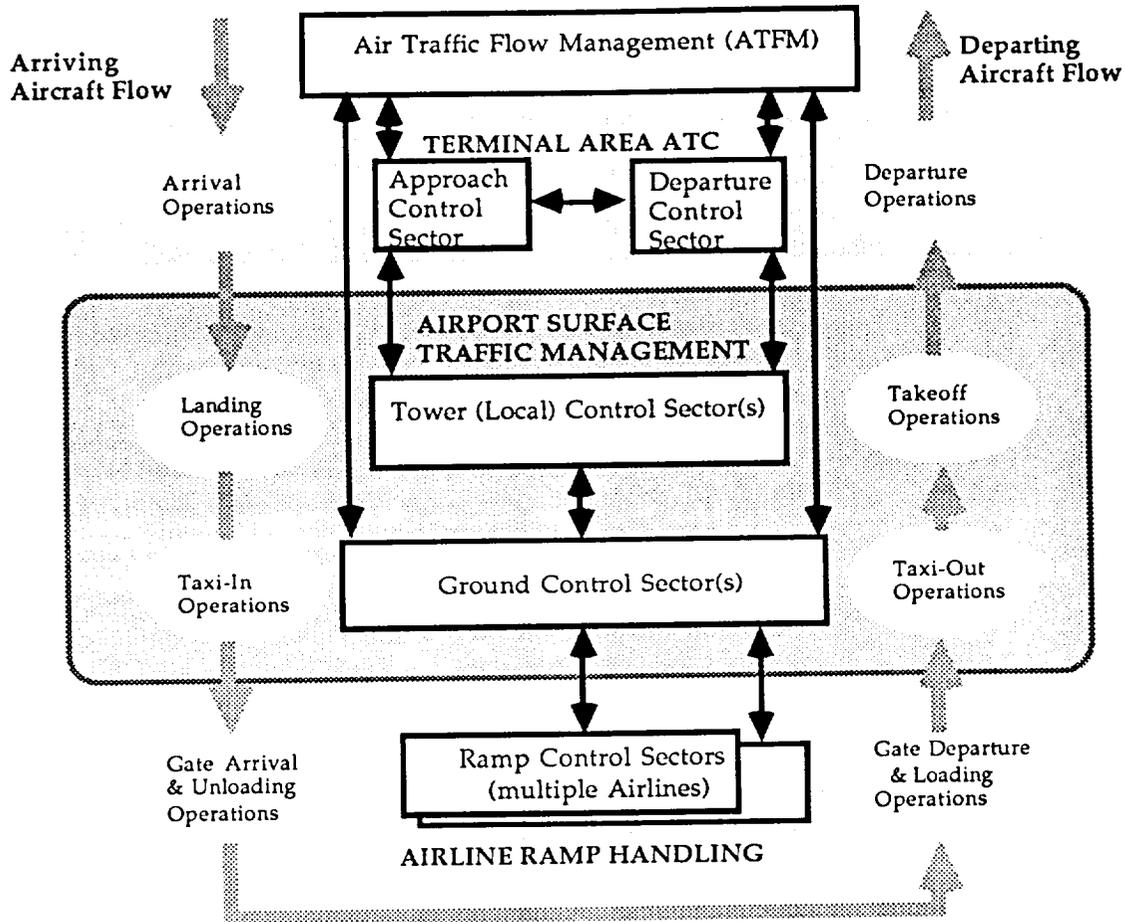
## **2.4 - A Generic Description of Airport Surface Traffic Management Processes**

The interrelationships between various ATC and ASTM processes is shown in Figure 2. As traffic flow rates approach capacity rates, these processes cannot remain independent and are forced to work together to achieve Congestion Management. In the following discussion the items of information which they must supply to each other in such circumstances are identified as their activities are described. There are two different aircraft traffic flows as mentioned above: the flow of arriving aircraft which starts before landing and results in the Taxi-In flow on the inbound taxiway route structure; and the flow of departing aircraft which starts before gate departure and results in the Taxi-Out flow on the outbound taxiway route structure.

### **2.4.1 - The Arrival Flow of Aircraft**

The existing ATC processes of Enroute ATC, Terminal Area ATC, and ATFM control the arrival flows of aircraft at the airport in response to forecasts of its landing capacity. From the ATFM process an initial rough estimate of Estimated Time of Arrival at the planned Entry Fix (ETAF) can be provided and updated from time to time whenever a significant change is noted. From the Terminal Area ATC process, an assignment to a landing runway and an Estimated Landing Time (ELT) can be provided with roughly 30 minutes warning. Both of these items are subject to change until a few minutes before landing, since there could be an unexpected change of Runway Configuration. ETAF and ELT are the parameters needed by ASTM from the ATC processes. There is a high degree of uncertainty in their values at any point before actual landing. Missed approaches or aborted landings further increase uncertainty.

FIGURE 2 - INTERRELATIONSHIPS OF ATC & ATSM PROCESSES



The runway exit which the pilot will elect to use and the time of arrival at that exit can be estimated (ETX) as a function of runway surface conditions, aircraft type, wind, visibility, etc., but is also subject to considerable uncertainty. While the Ground Control Sectors of ASTM can do some preliminary surface traffic planning, the decisions on the inbound traffic routing can only start when the aircraft actually enters the runway exit at the actual time of exit (ATX). This event will be obtained from airport surveillance after it happens.

To plan a routing, Ground Control also needs the gate assignment (or ramp area) to which the aircraft has been assigned by the Ramp Control process. By providing an estimate of landing times (ELT) to Ramp Control, and perhaps an initial Forecasted Time of Arrival at the Gate or Ramp Area (FTAG), Ground Control expects to receive back an assigned gate and its Estimated Time of Gate Ready (ETRG). This exchange can occur before landing, so that at ATX the ASTM process can quickly determine the taxiway routing and provide a new Estimated Time of Arrival at the Gate (ETAG) for Ramp Control. If ETRG exceeds ETAG by some amount, Ground Control may have to plan a different route to some area of the airport where aircraft can be held clear of the Ramp Area during their Taxi-in. Again there is some uncertainty in the estimate for ETRG, since it depends on the expected performance of various gate departure activities by Ramp Control. Ramp Control may change the Gate Assignment depending on whose actual progress.

### 2.4.2 - The Departing Flow of Aircraft

A variety of Ramp activities prepare an aircraft for pushback from the gate (flight planning, weight and balance planning, cabin cleaning, loading of cargo and passengers, loading of catering supplies, snow removal, refuelling, readiness of pushback crews and equipment, repair of minor faults in aircraft equipment, etc.). It is difficult to provide with a high degree of confidence, the estimated time of being ready for pushback (ETRP) which is required by ASTM. At some point, the actual time of being ready to pushback (ATRP) can be announced by Ramp Control. It may be accompanied by a request for a latest time of pushback clearance (LTCP) so that a gate can be cleared for an arriving aircraft.

Given these items of information, ASTM can plan an estimated time of pushback clearance (ETCP), an aircraft routing to an assigned takeoff runway (which could involve an assignment to a holding area somewhere on the airport surface), an estimated time of arrival at the takeoff runway (ETRA), and an estimated time of takeoff (ETTO). To do this planning, estimates are required from Terminal Area ATC and Tower Control on the capacity of arrival and departure flight operations and their current and planned backlogs; and from the ATFM process, information is needed on possible Ground Holds caused by traffic congestion at the destination airport of each individual flight. There is a high degree of uncertainty in all these estimates, and significant updates will occur with actual progress of runway operations and with changes in runway configuration, weather, etc.

Under certain situations where there is a lack of capacity in the Departure sectors of ATC, it becomes desirable for Ground Control to provide a certain sequence for takeoff aircraft. Rather than have a series of aircraft all departing southbound, for instance, departure capacity is increased by providing an alternating sequence of southbound and northbound aircraft. An aircraft destined for some takeoff runway may be instructed to wait at some taxiway intersection until another aircraft can pass it and precede it in the takeoff sequence. While this can be pre-planned as part of the runway assignment process, it will become part of the tactical control of aircraft movements on the airport surface, as described below.

### 2.4.3 - Separation Assurance for Surface Traffic

The surface traffic routings for all aircraft and ground vehicles can be supplemented with estimated times of arrival at intersections which would then allow an indication of possible conflicts between them. As mentioned above there is a wide variation in taxi speeds amongst pilots and no limitations imposed on planned taxi speeds at present. Under such situations, there is a high degree of uncertainty in predicting taxiway conflicts over a longer time horizon. This results in today's application of "Free Taxi" where a very short-term tactical concept is used for Separation Assurance. It is possible to conceive of an automated **Surface Collision Avoidance System (SCAS)** which would use good surface surveillance to provide a very short-term alert (15 seconds) to pilots and Ground Controllers about impending encounters. It would be useful in very bad visibility conditions which occur rather infrequently at most airports.

There are taxiway layouts which can result in "gridlock" if Ground Control does not carefully organize the sequence of aircraft movements. Usually these occur at the entry points to the Ramp from the circumferential gate taxiways where inbound and outbound flows cause multiple aircraft to meet each other at complex taxiway intersections.

### 3.0 - New Technological Capabilities for ASTM

There are a number of new technologies which have the potential to streamline surface traffic operations and improve safety at major airports. The FAA's ASTA program (References 2, 3, 4) incorporates most of these in four stages of implementation, as shown in Table 1.

#### 3.1 - Surface Surveillance

Until recently, surface surveillance in most major airports relied exclusively on visual contact. Twelve had a primitive Airport Surface Detection Equipment (ASDE) radar, ASDE-2, airports which was hampered by display clutter and difficulty of maintenance. This situation is being improved by the introduction of ASDE-3 at about 40 major airports; the system is expected to provide consistent high-quality radar surveillance of the airport surface. The data produced by the system is also suitable for computer analysis, facilitating automatic conflict-detection software and eventually traffic management aids. While this solves the problem of locating aircraft on the surface, it does nothing to identify them; all aircraft look identical on the display. In order to address this shortcoming another system is required; the most popular option to date has been a Mode-S Beacon system.

Complex Mode-S beacon systems are already in use for en-route and terminal surveillance; a surface implementation would be simpler, consisting only of five to seven antennas and associated electronics placed around the edge of the airport. The system receives the signals emitted by an aircraft's Mode-S transponder, which include the identity of the aircraft, and use differences in reception time at the various antennas to fix its location. This allows for a tower display showing the location and identity of all surface aircraft equipped with Mode-S transponders. Aircraft not so equipped would register on ASDE-3 and appear on the display without identification.

Another system which is now being considered is the Differential Global Positioning System (DGPS), which uses satellites to determine an aircraft's position in a manner similar to the use of the antennas in the Mode-S beacon system. This system has high precision and is already being used for ground and sea transportation, but it would require retrofitting aircraft with DGPS transmitters and receivers.

**Table 1. Stages in the FAA's ASTA Program**

AMASS	Audible Alerts in Tower ASDE Display Enhancements
ASTA-1	Runway Status Lights Runway Status on ASDE Display
ASTA-2	Data Tags on ASDE Display Departure Sequencing Aid Taxi-Route Compliance Monitoring Airport Configuration Management Aid
ASTA-3	Surface Traffic Data in Cockpit Audible Alerts in Cockpit Active Taxi-Route Guidance Traffic Planning Aid

### 3.2 - Automatic Alerts

AMASS includes software which constantly evaluates the surface traffic situation as described by the ASDE-3 radar and creates an audible alarm in the tower when a hazardous situation develops. It is hoped that this will attract the controller's attention to the situation early enough to avert a collision. Once digital data links are implemented as described below, it will also be possible to have automatic conflict alerts sound directly in the cockpit, saving the time it would otherwise take for the controller to assess the situation and communicate it to the pilot. For both kinds of automatic alerts, the ideal system would detect all genuine conflicts and yield no false alarms or "nuisance alarms" (alerts sounded because the alerting criteria are violated while there is no true risk of a collision) although any real-world system will at best approximate these properties.

### 3.3 - Runway Status Lights

The automatic conflict alerts in AMASS are useful for detecting potential collisions and resolving them but do little to prevent conflicts in the first place. To this end, ASTA-1 includes a system of two kinds of runway status lights. The first set of lights are runway-entrance lights, placed wherever a taxiway intersects a runway. The lights indicate to aircraft on the taxiway whether or not it is safe to cross the runway. The second set of lights are takeoff-hold lights, indicating to aircraft at the beginning of a runway whether or not they are cleared for takeoff. In order to keep controller workload low, these lights are operated automatically; a complex algorithm analyzes surveillance data to determine which crossings and runways are clear and operates the lights accordingly. The system is not designed to replace clearance from the controller, merely to supplement it. Clearly, the light management system must be carefully designed so as to agree with the controller on when it is safe to cross a runway or take off in order to avoid confusing the pilot with contradictory clearances.

### 3.4 - Digital Communications

The introduction of digital datalinks to provide data transfer between ground computers and aircraft computers is a source of many potential ASTA enhancements. These datalinks could use VHF and UHF radio, Mode-S, or satellite links. Some functions which are currently done by voice channel, such as taxi route clearance and compliance monitoring, could be accomplished more efficiently through digital data transfers. This would clear the chatter on the voice channels, streamlining operations and making it easier for the controller to get the pilot's attention. Other information which could be transferred via the data link includes weather data, direct cockpit conflict alerts, and delivery of surface traffic data to the cockpit. Providing the pilot with such information offers yet another chance to prevent conflicts after the controller and the automatic light system have evaluated the situation, as well as helping the pilot to understand overall events on the airport surface.

### 3.5 - Automated Planning Aids

With the advent of surveillance tools such as ASDE-3 and the Mode-S beacon system, it is possible to create computer programs to help manage surface traffic flow. ASTA-2 includes a departure-sequencing system which would make use of flight plan data and surface traffic conditions. ASTA-3 will include some form of traffic planning aid which will generate a tentative surface traffic plan for controller approval and coordinate

this plan with other ATC automation systems. Also possible are such tools as a runway configuration aid, designed to choose the ideal runway configuration given surface and air traffic data as well as organize transitions from one configuration to another.

### **3.6 - Computer Displays**

In order to make use of better information, new displays are needed. AMASS, in the case of a conflict, adds to the ASDE display information and is useful in resolving a hazardous situation rapidly. It also adds an *approach bar* to the display for each active runway, indicating the location of incoming aircraft. ASTA-1 incorporates the runway status information used to operate Runway Status lights. ASTA-2 is scheduled to include data tags on the ASDE display (probably obtained from a Mode-S system, although that has not been finalized). Design of cockpit computer displays will also become an issue as digital data-links allow for automated clearances and surface traffic data in the cockpit. Careful design of the cockpit display is needed since the pilot is being asked to share his attention between a heads-down computer display and looking out the window. The pilot should be able to quickly obtain pertinent information without being distracted by irrelevant data.

### **4.0 - Modeling Requirements**

Before initiating any plan to implement airport surface traffic automation on a large scale, it is important to verify that such automation is warranted. The FAA initiated the ASTA program with the aims of reducing the number of hazardous events and collisions on the airport's surface, the amount of delay suffered by aircraft on the airport's surface, and the workload of pilots and airport surface controllers. The nature of the problems in these areas should be evaluated carefully to make sure the changes being considered would result in a significant improvement over existing conditions. This calls for extensive modeling capabilities. A variety of models, both analytic and simulation, are needed for this purpose. Additional modeling requirements are imposed by the need to evaluate carefully the costs and benefits of ASTM systems. In this section we review some of the primary types of models that are needed, along with the capabilities they should possess.

One feature common to all of the models is applicability to a variety of airports. Because many airport surface problems are of a local nature and depend heavily on airfield configuration, it is highly probable that some of the ASTM tools to be developed will have to be location-specific, while some other tools may have to undergo extensive modification for adaptation to local conditions. The need for (and potential benefits from) advanced ASTM tools will also vary from airport to airport and it is conceivable that the benefits may not justify the costs at some or many airports.

### **4.1 - Conflict Avoidance and Accident Causality**

Some of the ASTM tools under consideration are primarily intended to either prevent conflicts on the airport's surface or to identify and resolve them well in advance. Most of these approaches are dependent on software and hardware which automatically recognizes a developing conflict and then initiates a process that would prevent an actual collision. It is important to note that identifying correctly a potential conflict on the airport's surface is far from an easy task. There are no speed requirements on taxiways, so aircraft move at the speed that the pilot feels is appropriate; this makes it difficult to predict the time at which an aircraft will reach a specific location. It is also probable that one of two aircraft predicted to encounter each other will change course or speed before the predicted encounter can occur, especially since, for the system to be of any use, the conflict must be identified early enough to allow for reaction time and in some cases communication. Clearly the potential for many "false alarms" exists in such an

environment. The capabilities required to evaluate such problems and issues should therefore include the modeling of various levels of uncertainty about (current and future) positions of aircraft, future intentions of aircraft, response and reaction times, etc. A high level of model flexibility is also necessary, so that many alternative scenarios along these lines can be explored.

In order to evaluate the safety benefits of a surface traffic automation measure, a good understanding and, if possible, a model of the causes of surface accidents is also needed; the data from a simulation incorporating the ASTM change made and the data from normal operations can then be used to compare the relative safety of the two modes of operation. The model should identify the factors leading to the occurrence of a conflict as well as the factors contributing to the chance of successful conflict resolution. It is important to define for these purposes exactly what comprises a "conflict". In studies to date, the cases considered have included both actual collisions and instances where controller intervention was deemed necessary to prevent one. This provides a set of data for analyzing the causes of a conflict; but the inclusion of cases of intervention may overstate the frequency of true safety hazards, as it is conceivable that some or many of these interventions may have been unnecessary ones or may even have themselves triggered a more serious conflict than would otherwise exist. Care must be taken that the model does not confuse perceived need for intervention with the true causes of potential accidents.

#### **4.2 - Cost Models**

While many of the automation measures mentioned in Section 3 are likely to have some positive effects, they also require money and effort to implement. In order to make informed decisions about the value of installing these systems, methods for valuing their costs and benefits are needed. In order to understand how various distinct groups benefit, separate models should be devised for airlines, passengers, and airports. Factors such as passenger delay time, aircraft delay time at the gate and during taxiing, and fuel used during delays should be assigned monetary values to determine the value of performance improvements. Most difficult, such factors as safety and controller workload should be brought into the picture somehow, preferably through the assignment of monetary values to them. The cost model for implementing changes should factor in research and development cost, testing, installation, revision of operating procedures, retraining for the new operating procedures, and maintenance of the new systems.

#### **4.3 - Human Factors**

Simulators are needed to study the interaction between the human operators and the automation systems. One simulator should represent the situation as seen from the tower and provide realistic surface traffic scenarios with an interface appropriate for the automation systems in use. Another simulator is needed for the pilot's perspective, providing an "external" view of the airport, communications, and data appropriate for the automation systems being simulated. These simulators should be adaptable to different operating procedures, display formats, airports, and operating conditions (such as rain, snow, low visibility, and configuration changes.) They should include factors which would complicate traffic scenarios in real airport operations, for instance human error and under-equipped aircraft (such as those lacking a Mode-S transponder or sophisticated display equipment, depending on the automation systems being simulated.) They should also be able to operate in real time even for high traffic situations and use both custom and randomly generated traffic scenarios. The simulator should also be able to record the data needed for safety, cost-benefit, and delays analysis, such as: response times; volume of communications; aircraft delays at the gate and during taxi; controller/pilot idle time;

frequency of pre-defined incidents; frequency of false alarms and nuisance alarms; frequency of misinterpreted communications and signals; etc.

In addition to studying human factors in ASTM, these simulators will be useful in obtaining a better understanding of some of the "side effects" of advanced ASTM. Reducing pilot and controller workload is desirable as much for its own sake as for its impact on other ASTM concerns. For example, a decrease in controller workload might lead to a reduction in controller errors, thus improving safety, or in more efficient operations as a result of more time to consider delay-reducing strategies for airport surface operations.

#### **4.4 - Fast-time Simulator**

Finally, a fast-time simulator is needed in order to yield data for the analysis of capacity, delays and costs. This is essentially a high-speed version of the software used to generate situations for the human factors model, with the behavior of both the controller and the pilot being simulated instead of just one. However, with the emphasis on metrics like capacity and delays, a somewhat lower level of detail and realism than in the case of the human factors simulation can be tolerated. On the other hand, in the absence of a simulated pilot or controller interface, care must be taken to make the fast-time simulator account for communication and response time; plans do not take effect the instant after they are conceived in the real world, so they should not do so in the simulation either. It is also important that the simulator be able to portray unusual conditions; the performance of an automation system will change in the presence of special procedures such as runway configuration changes, de-icing, snow removal, and poor visibility.

Furthermore, since detailed data are desired on the performance of the system as a whole, the overall ATM system must be represented more accurately than is necessary for the human factors simulators. For example, the simulator should be able to model integrated approaches to delay reduction that consider simultaneously gate, apron, taxiway and runway delays. One implication of this is that the simulation should not only be able to incorporate models of ASTM systems and algorithms for reducing delay, but must also be able to capture the interactions of these systems and algorithms with other terminal area automation systems, such as future versions of CTAS, that would co-ordinate operations on the runway system. Similarly, if they are to function properly in gate and apron areas, ASTM systems and algorithms should interact closely with airline information systems and that effect should be captured by the simulation model. Clearly, these requirements will not be easy to satisfy.

In addition, as noted earlier, there is a great deal of uncertainty in predicted arrival times and the timing (or even existence) of anticipated surface encounters, so the associated processes in the simulator should include random variation in order to test how the automation system handles uncertain quantities. The limits placed on the planning horizon of the automation system by this uncertainty are also of interest; the simulator should output data on the average and minimum buffers between the formulation of a plan and the occurrence of the events it manages. Related to this is the number of times a plan has to be modified due to dynamically changing circumstances. A plan formulated well in advance will probably go through several revisions, making it more difficult for the controller to remember the current plan of action; information on the frequency of plan revisions should therefore be output as well. Without these features, the simulator would model a far more idealized world than the real one for which automation systems are ultimately intended.

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## List of Acronyms

- ASDE Airport Surface Detection Equipment
- ASTA Airport Surface Traffic Automation
- ASTM Airport Surface Traffic Management
- ATFM Air Traffic Flow Management
- ATRP Actual Time Ready for Pushback
- ATX Actual Time at Runway Exit
- DGPS Differential Global Positioning System
- ELT Estimated Landing Time
- ETAF Estimated Time of Arrival at Entry Fix
- ETAG Estimated Time of Arrival at the Gate
- ETCP Estimated Time of Clearance for Pushback
- ETRA Estimated Time of Arrival at the Takeoff Runway
- ETRG Estimated Time of Gate Ready
- ETRP Estimated Time Ready for Pushback (ETRP)
- ETTO Estimated Time of Takeoff
- ETX Estimated Time at Runway Exit
- FTAG Forecasted Time of Arrival at the Gate
- LTCP Latest Time of Clearance for Pushback
- SCAS Surface Collision Avoidance System

## Appendix C

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### WWW Resources:

#### Model homepages:

##### U.S.:

TAAM, Total Airspace & Airport Modeller (Embry-Riddle)  
[http://erau.db.erau.edu/~taam/tpg\\_taam.html](http://erau.db.erau.edu/~taam/tpg_taam.html)

MIDAS  
[http://ccf.arc.nasa.gov:80./af/aff/midas/MIDAS\\_home\\_page.html](http://ccf.arc.nasa.gov:80./af/aff/midas/MIDAS_home_page.html)

ASAC Charts and Spreadsheets  
<http://www.asac.lmi.org/archive.html/#Charts>

##### Europe:

Annette WWW Demonstrator  
<http://daedalus.dra.hmg.gb/annette/>

BADA WWW Demonstrator  
<http://daedalus.dra.hmg.gb/annette/bada.html>

Eurocontrol WWW home page  
<http://www.eurocontrol.fr/>  
<http://s4dc8isd.eurocontrol.de/>

Le projet MUFTIS  
[http://www.cenaath.cena.dgac.fr/~klrz/public/Projet\\_MUFTIS.html](http://www.cenaath.cena.dgac.fr/~klrz/public/Projet_MUFTIS.html)

HIPS Home Page  
<http://robin.uneec.eurocontrol.fr/hips/>

Eurocontrol Experimental Centre  
<http://castle.uneec.eurocontrol.fr/>

DRA - Open Distributed Systems  
<http://daedalus.dra.hmg.gb/>

DERA  
<http://www.dra.hmg.gb/>

NARSIM Home Page  
<http://www.nlr.nl/public/fac/narsim/index.html>  
<http://www.nlr.nl/public/fac/narsim/airmod.html>

DLR - German Aerospace Research Establishment  
<http://www.dlr.de/>

#### AATT Homepages:

MIT/AATT :  
<http://web.mit.edu/aeroastro/www/labs/AATT/>

NASA/AATT:  
<http://www.nas.nasa.gov/AATT/>