

# AN AGENT-BASED MODEL OF THE AIRLINE INDUSTRY

**William Niedringhaus**  
The MITRE Corporation<sup>1</sup>  
1820 Dolley Madison Blvd.  
McLean, VA 22102  
wniedrin@mitre.org

## 1 Introduction

The Air Carrier Service Evolution Model (ACSEM) is an agent-based model that explores the evolution of the airline industry and its interactions with the US National Airspace System (NAS). ACSEM models airline decisions such as markets (what airports to serve and where to establish hubs), fleet mix, schedules, fares, and airline responses to delays, congestion and missed connections. ACSEM also models decisions by the Federal Aviation Administration (FAA) or individual airports, related to airport hourly capacities and possible reductions imposed due to weather or congestion.

Because these factors both affect and are affected by each other, understanding their complex interaction is beyond the ability of traditional modeling tools and has not been attempted until now. The problem is difficult enough thanks to the sheer numbers involved: thousands of aircraft and millions of possible flight connections. But the main source of difficulty is the

---

<sup>1</sup> ©2000 The MITRE Corporation. All rights reserved. This is the copyright work of The MITRE Corporation and was produced for the U.S. Government under Contract Number DTFA01-93-C-00001 and is subject to Federal Acquisition Regulation Clause 52.227-14, Rights in Data-General, Alt. III (JUN 1987) and Alt. IV (JUN 1987). No other use other than that granted to the U.S. Government, or to those acting on behalf of the U.S. Government, under that Clause is authorized without the express written permission of The MITRE Corporation. For further information, please contact The MITRE Corporation, Contracts Office, 1820 Dolley Madison Blvd., McLean, VA 22102, (703) 883-6000.

entangled web of interactions with multiple feedback loops. Using agent-based modeling techniques, it is now feasible to build a model such as ACSEM to address aspects of airline/NAS evolution.

There are a number of interesting potential uses for such a model. It could be run to evaluate the impact of possible policy changes, such as adoption of Free Flight<sup>2</sup> concepts. It could help analyze future possibilities such as a new runway or airport, invention of a new type of jet, a change in operational costs, an improvement in the NAS's ability to predict aircraft arrival times, removal of certain ATC restrictions (thereby shortening travel times), or changes in passenger demand. Another area of interest to the FAA is understanding the conditions under which airlines form primary and/or secondary hubs. Questions of interest include whether and when such hubs can be shared among airlines, and whether they require alternating banks of arrivals and departures, or whether a continuous mix suffices. Since passenger demand is growing rapidly with only limited possibilities for airport capacity growth, understanding all of these issues becomes increasingly important.<sup>3</sup>

Airline agents in ACSEM use simple rules to decide on values for operational characteristics such as fares, aircraft size and flight departure times. Over thousands of iterations, these actions cause a rich variety of complex behaviors to emerge in the model—behaviors which are observed in real airlines such as banking and hubbing, regionalism, market niches and price wars.

This paper presents some early results obtained by ACSEM. The model scenario consists of 1,668 aircraft flown recently in actual operations in the Northeast US, and illustrates how certain complex behaviors emerge. The results suggest mechanisms that may some day lead to improvements in the NAS for facilitating more efficient air travel and NAS operations.

## **2 Modeling the Airline Industry and National Airspace System (NAS)**

As with any simulation, ACSEM developers needed to decide which features of its NAS domain to model explicitly, which to model implicitly, indirectly or coarsely, and which features not to model at all. Airlines, of course, maintain whole research departments to make strategic and tactical decisions regarding fleet, fares and schedules. ACSEM does not try to

---

<sup>2</sup> RTCA (1995), *Report of the RTCA Board of Directors' Select Committee on Free Flight*, Washington DC, January 1995

<sup>3</sup> ACSEM has its origin in another agent-based airline model, IMPACT, whose focus is more narrow: airline collaborative decision making when weather disrupts schedules: see Campbell et. al., "Modeling Distributed Human Decision-Making in Traffic Flow Management Operations", 3<sup>rd</sup> USA/Europe Air Traffic Management R&D Seminar, Naples, Italy, June 2000. IMPACT in turn was preceded by lower-fidelity agent-based models (e.g., see Klein, G.L. and Anton, P.S. (1999), "A Simulation Study of Adaptation in Traffic Management Decision Making under Free Scheduling Flight Operations," *Air Traffic Control Quarterly* 7(2), 77-108).

emulate this aspect of the airline industry. Following the approach of Epstein and Axtell<sup>4</sup>, it models a simplified world, but retains enough richness to express many possible airline strategies. Section 2 discusses how ACSEM models airlines and NAS; Section 3 addresses the tools airlines use in ACSEM to learn to make economic decisions.

## 2.1 Inputs and Outputs

ACSEM's **input** consists of (following such sources as Jenkins<sup>5</sup>)

- general economic conditions, such as interest rates and availability of venture capital
- a set of airports to model in detail—their capacity (e.g., arrivals/departures per hour) and population served
- peripheral regions to model in less detail
- demand function between each airport-pair, for two types of passenger (leisure and business)
- costs of owning/operating aircraft of various types (both on ground and in air)
- a starting schedule—a set of airlines, their aircraft, and their scheduled itineraries, arrival/departure times and fares

ACSEM's **output** consists of

- a finishing schedule—the airlines, aircraft, scheduled itineraries, arrival/departure times and fares
- airline metrics such as profits, load-factors, revenue passenger-miles
- NAS performance metrics such as passengers serviced and average delay

The starting schedule can be derived from real traffic, or can be synthesized or empty. When ACSEM starts with a real schedule from, say, five years ago, and the input costs and demands match those in effect today, we would hope to see the final schedule in some sense resemble today's—in fact, validating ACSEM is largely a matter of defining and verifying this resemblance. If the input costs and demands are different, perhaps representing values for five years in the future, ACSEM's output is intended to suggest changes one might expect in the future. The model would be run many times (with many random seeds); details will vary but significant fundamental trends tend to emerge. Spotting and understanding such trends is the major goal of ACSEM.

## 2.2 Modeling Aircraft

In ACSEM, aircraft are characterized by a single parameter, which controls their capacity (seats) and costs, including those of ownership and maintenance, fuel and operation, which are modeled to grow as a function of the capacity.

---

<sup>4</sup> Epstein, J. M and Axtell, R (1996), *Growing Artificial Societies: Social Science from the Bottom Up*, Cambridge, MA: MIT Press.

<sup>5</sup> Jenkins, D, ed. *Handbook of Airline Economics*, New York, NY: McGraw Hill

### **2.3 Modeling Flights**

Given the schedule, ACSEM determines a list of ways for passengers to travel for each origin-destination airport pair. This is a simple process for direct flights involving a single aircraft. For origin-destination pairs not served adequately by direct flights, ACSEM determines a list of the most reasonable transfer flights, on a single airline or (if there is still no adequate service) on two different airlines.

### **2.4 Modeling Passengers and Demand**

Passengers are modeled as “Passenger-Sets”—sets of people with a similar goal: getting from one airport (the origin) to another (the destination). They may also have strong or weak preferences for particular times of day.

### **2.5 Leisure and Business Passengers**

Passengers and Passenger-Sets are of two types: Leisure (generally valuing low cost over convenience) and business (generally valuing the reverse). The former buy tickets early to get a reduced fare. The business passengers are modeled to buy their tickets later. The airlines quote different fares for each. Real airlines have many different fares, but ACSEM models only these two. The airlines reserve a certain number of seats for business passengers, refusing to sell them early to leisure passengers in hopes of greater profits.

### **2.6 Selling Tickets**

Each Passenger-Set considers all the flights from its origin to its destination. For each flight, ACSEM calculates a net value perceived by the Passenger-Set, equal to a gross value minus the fare. The “perfect” flight—which departs at the preferred time and takes the minimum time, is assigned the highest gross value. For a flight that leaves at a different time, or takes longer than the minimum possible time, the gross value declines proportionately. Passenger-Sets do not all try to buy seats on the highest-ranked flight; ever-smaller fractions will prefer the second-ranked, third-ranked, and so on. The idea is that a Passenger-Set represents a diversity of people with a common set of goals who can be treated statistically.

### **2.7 Simulating a Day of Air Traffic: Congested Airports and Missed Connections**

Once all passengers who wish to buy tickets do so (given the current fares on the current routes), ACSEM simulates the aircraft flying their routes. When two or more aircraft try to arrive at or depart from an airport with limited capacity, they queue up, first come first served. If an aircraft is thereby delayed, it tries to get back on schedule by minimizing its ground turnaround times as it progresses through its itinerary. In the meantime, some transferring passengers may miss their connections.

The tradeoffs between direct and transfer flights is fundamental to understanding economic payoffs both for the airlines and their customers. To service  $M$  airports using direct flights requires  $O(M^2)$  flights, but only  $O(M)$  with transfers. Counterbalancing this potentially more

efficient use of aircraft are the complications induced by transfers. These include longer transit times for passengers, the need for tightly orchestrated schedules by airlines, and an increased vulnerability to small schedule disruptions which may trigger a cascade of missed connections throughout the day.

ACSEM treats passengers who have missed their connections in a simple way—the airlines forfeit a percentage of these passenger’s fares. Of course, in the real world, it is much more complicated—airlines divert or cancel flights, use busses, hotels, etc. The authors feel that ACSEM’s simplification captures the essential economic result for the airlines—missed connections cause airlines lost revenue.

### **2.8 Passenger Response to Late Arrivals**

ACSEM uses a similar simplification to express passenger response to late arrivals—the airlines forfeit a percentage of those passenger’s fares. This percentage increases with the delay. Again, in the real world events are quite different and more complex—passengers switch to a different airline next time or take some other form of transportation, and they may criticize the airline to their friends, etc. Again, the authors feel that ACSEM’s simplification captures the essential economic result for the airlines—late passengers cause airlines lost revenue.

## **3 How the Airlines Make Decisions : ACSEM’s Learning Tools**

We next discuss the learning tools ACSEM’s airline agents use to make economic decisions. These tools form the heart of the ACSEM simulation. The tools involve an airline taking an economic action of a specific type (e.g., raise fares or buy an aircraft), and determining whether the tool’s action has a positive result. If so, the airline reinforces/intensifies/extends the tool’s action (raises fares some more, buys more aircraft), but if not, the airline reverses/retracts the tool’s action (lowers fares, avoids buying aircraft). The tools can be divided into three categories, continuous, discontinuous, and personality, depending on the type of economic action.

### **3.1 Continuous tools**

Using Continuous tools, the airlines’ action is to learn a value for a real-numbered parameter, such as a fare or a departure time. Continuous tools begin by taking small changes, and if a trend is spotted, ever larger changes. Each tool typically must be run several times consecutively, enough to spot and exploit any trends. The Continuous tools include:

- **BUSI\_FARE and LEIS\_FARE:** Airlines adjust business/leisure fares for each airline and origin-destination served. The tradeoff is the classical economic interplay of supply and demand, governed partly by passenger demand elasticity as input to ACSEM.

- **BUSI\_FRAC:** Airlines adjust the fraction of seats reserved for business passengers, as discussed in 2.5, for each leg of each aircraft's itinerary. The tradeoff is the degree to which an airline accepts a sure leisure passenger or gambles instead on a potential (but more lucrative) business passenger.
- **RESIZE:** Airlines adjust the number of seats for each aircraft. The tradeoff is extra seats to sell, versus the increased costs of owning/maintaining larger aircraft.
- **DEPART\_TIME:** Airlines adjust scheduled depart time, for each leg of each aircraft's itinerary. The tradeoff is complex, involving passenger's preferred depart times and opportunities for passenger transfers
- **ARRIVE\_TIME:** For each depart time, the airlines determine an arrive time. The minimum is (depart time + minimum flight time), but airlines usually find it in their interest to pad this value, in anticipation of delay.

### 3.2 Discontinuous tools

Using Discontinuous tools, the airlines perform specific actions, such as buying or selling an aircraft. The action is performed  $N$  times, where  $N$  is an integer, and the tool tries to learn a reasonable value for  $N$ .  $N$  grows with repeated success. ACSEM's Discontinuous tools include:

- **AC\_BUY:** Airlines purchase  $N$  aircraft. Each is assigned a simple two-airport itinerary, chosen by a heuristic that looks for unmet passenger demand.
- **AC\_SELL:** Airlines sell the  $N$  aircraft with the worst losses or lowest profits.
- **CHANGE\_ITINERARY:** Airlines modify the itineraries of  $N$  of their aircraft, by adding or dropping an airport.
- **AIRPORT\_OFFICE:** Airlines may choose to initiate service at an airport not previously served.
- **SCHEDULE\_SWAP:** For each airport served, airlines determine if a departure leaves just before another aircraft arrives. If so, the airline considers moving the arrival ahead of the departure, to allow for a passenger transfer.

### 3.3 Personality tools

Using Personality tools, ACSEM's airline agents determine how to weight various factors (besides profits) such as market share and on-time percentage to create an *objective function*. Thus, the purpose of the personality tools is to learn how to learn, sometimes called meta-learning. To evaluate the personality tools themselves, the airlines use their ultimate objective, which is pure profits. To evaluate all other learning tools the airlines use the objective function determined by the personality tools. The Personality tools are relatively new in ACSEM. They show promise: for example, airlines have evolved which learn to increase market share. Once they have built up market share, their "personality" reverts to maximizing short-term profits.

## 4 Simulation Results

This section presents results from the ACSEM simulation. The first example is given mainly to illustrate how ACSEM, with very little economic knowledge programmed in, generates airlines that follow a succession of different but appropriate economic strategies as conditions change. The second scenario, shown in the figures, explores the evolution of a 1,668-aircraft SCENARIO derived from real traffic in the Northeast US.

### 4.1 Analysis of Fares in Two-Airport Market: One and Two Airlines

A two-airport, four aircraft scenario was run twice, once with a single airline, and once with two airlines owning two aircraft each. The aircraft start at Airport B, fly to Airport A at 5-minute intervals, and 100 minutes later, fly back to B. The business and leisure fares are initialized to \$1.00 and \$0.30 per nmi, respectively, with 20 of each aircraft's 100 seats reserved for business. Passenger demand is allowed to increase 25% every 50 cycles. The only learning tool applied is LEIS\_FARE, so that BUSI\_FARE and BUSI\_FRAC are fixed.

When one airline owns all 4 aircraft, it follows several distinct strategies as demand increases. Initially, there is an oversupply: both business and leisure seats remain unsold. Leisure fares stay roughly constant. The number of unsold business and leisure seats gradually declines until there are no leisure seats left. The airline then begins raising leisure fares sharply. Meanwhile business demand also increases until all 20 business seats are sold. The airline would like to sell more business seats (they are more lucrative). Although it cannot change BUSI\_FRAC, it finds another way: it increases leisure fares to the point where exactly enough leisure seats are unsold to match the (still growing) business demand. Eventually the leisure fare exceeds the (artificially-fixed) business fare, and the airline policy changes again. The leisure passengers are now more lucrative than business passengers, so the leisure fare soon evolves to the highest level at which exactly 80 leisure seats are purchased; the rest are reserved for and sold to business passengers.

When two airlines each own two of the four aircraft, the pattern is quite different. In the early, light-demand phases, the two airlines engage in price wars and exhibit wide swings in profits and market share. The loser flies virtually empty planes. Later, as demand increases, the airline winning the price-war fills its seats and makes a reasonable profit, while the airline losing the price-war gets customers anyway, because the winner can't meet the entire demand. The loser actually feels pressure to raise fares somewhat, since the (luckless) passengers flying on it don't have anywhere else to go. Finally the demand increases to the point where the "price-war loser" plane is nearly full, and the "loser" sometimes actually makes more profit than the "winner". Finally, both airlines sell all their seats, charge roughly equal fares, and the airlines' strategies resemble those seen during the last phases of the one-airline scenario

#### **4.2 Airline Industry/NAS Response to Different Airport Capacities; Different Operational Costs**

The figure shows ACSEM results generated from a set of 1,668 aircraft flying in the northeast United States on a clear day in October 1998. The airports modeled lie in a rectangle from 82 to 67 degrees West longitude, and from 38 to 47 degrees north longitude (West Virginia to Maine); with peripheral regions extending west to Chicago. Each was run 2000 cycles and settled into a steady state. Three runs are shown, in which the capacities of airports (arrivals/departures per hour) are assumed to be 30, 60, and infinite.

### **5 Next Steps**

The ACSEM simulation shows promise in providing new insights into the possible evolution of the airline industry and the NAS—a task featuring multiple feedback loops difficult to address using traditional techniques. The enabling factor is ACSEM's use of agent-based modeling.

Currently ACSEM is undergoing validation testing to assure its predictions are consistent with those of airline industry experts under various controlled conditions. Tests are also underway on a large northeast-US scenario from the recent past with more than 3,000 aircraft, to determine how well ACSEM is able to reproduce today's traffic given today's economic conditions such as operational costs and passenger demand. Early results, such as those reported here, look promising. If ACSEM continues to test well, it may soon lend valuable insights into the future of the airline industry and the NAS.

