Validating The Airspace Concept Evaluation System Using Real World Data

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This paper discusses a process for validating the Airspace Concept Evaluation System using real world historical flight operational data. ACES inputs are generated from select real world data and processed to create a realistic reproduction of a single day's operations within the National Airspace System. ACES outputs are then compared to real world operational metrics and delay statistics for the reproduced day. The results indicate that ACES produces delays and airport operational metrics similar to the real world with minor variations of delay by phase of flight. The results also illustrate how independently designed models may interact in ways that were not intended.

I. Introduction

A. Background

The Airspace Concept Evaluation System(ACES) is a National Airspace System(NAS)-wide fast-time simulation tool developed at NASA Ames Research Center.[1] ACES models and simulates the NAS using interacting agents representing center control, terminal flow management, airports, individual flights, and other NAS elements. These agents pass messages between one another similar to real world communications. This distributed agent based system is designed to emulate the highly unpredictable nature of the NAS, making it a suitable tool to evaluate current and envisioned airspace concepts.

To ensure that ACES is producing the most realistic results, the system must be validated. There is no way to validate future concepts scenarios using real world historical data, but current day scenario validations increase confidence in the models and the validity of future scenario results. Each operational day has unique weather and traffic demand schedules. The more a simulation utilizes the unique characteristic of a specific day, the more realistic the results should be. ACES is able to simulate the full scale demand traffic necessary to perform a validation using real world data. Through direct comparison with the real world, models may continue to be improved and unusual trends and biases may be filtered out of the system or used to normalize the results of future concept simulations.

There have been many domain specific attempts at simulation validation using real world data such as with noise impacts[2] and airport operations[3] models. Very few system-wide simulations being developed today have published simulation validation results. One system-wide scale simulation that has performed some validation using real world data is MITRE's Jet:Wise.[4] Jet:Wise is an agent based simulation of airline activity designed to predict future airline trends. The inputs include observed fleet mix, schedules, and fares from historical data. Validation outputs consist of observed passenger counts tested against each of the various airlines, routes, and markets.

Similar methods are used to validate ACES from an airspace operations standpoint. Weather and traffic demand schedules serve as ACES inputs. ACES outputs are then compared to real world operational metrics and delay statistics to conduct the system validation.

B. Summarizing The Process

The validation process involves extracting both ACES inputs and output comparison data from real world data. Figure 1 shows a diagram of the basic validation process. ACES inputs from real world data included

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flight plans and airport capacities. ACES outputs to be compared with real world data included airport throughput rates, delay statistics, and individual flight tracks.

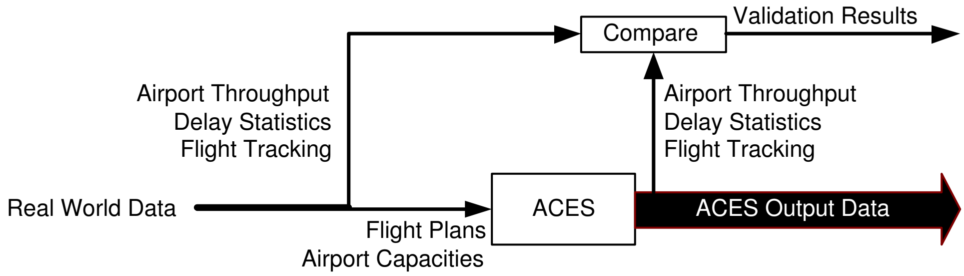


Figure 1. Diagram of the ACES validation process.

ACES requires various input data to simulate the unique weather and traffic demand schedules representing a given day in the NAS. A demand schedule and set of flight plans are compiled by combining information from various NAS messages for each flight. The NAS messages are available through Aircraft Situation Display to Industry (ASDI) data.[5] Although ACES does not model weather explicitly, ACES is able to model the effects of weather in the form of varying airport capacities throughout the day. These airport capacities are extracted from Aviation System Performance Metrics (ASPM) data.[6]

ACES models vary in fidelity and complexity. For an initial validation of the system, only the most basic functionality is utilized. This functionality includes lateral enroute delay maneuvers, minimum separation at departure meter fix crossings, airport and sector constraints, and using winds.

As agents representing elements of the NAS interact, ACES collects every message passed between them such as aircraft state messages and flight time messages. The data extracted from these messages may be as detailed or high level as the research requires. Thus validation comparison is limited only by the fidelity of the ACES models being used and real world data availability.

ASPM provides high level summary statistics at major US airports which may be compared to ACES scheduled and actual throughput levels at those airports. Throughput comparisons show that ACES throughput levels are comparable to that of ASPM. The Bureau of Transportation Statistics (BTS) provides delay statistics for individual flights for certain airlines. These flight delays may be compared with their ACES counterparts. The results show comparable delays with minor variations in phase of flight. Finally, individual flight NAS tracking messages from ASDI may be compared with ACES aircraft state information to validate individual flight trajectories. ACES models individual flight trajectories extremely well when the real flight follows the flight plan. Deviations occur when the real flight modifies it's original flight plan with direct-to segments.

II. Preprocessing ACES Inputs

ACES requires various types of inputs to simulate a realistic day in the NAS. Static inputs include center and sector boundaries and capacities, airport locations, and unimpeded airport taxi times. These inputs do not change often and only need occasional updating. Other inputs such as the schedule of flight plans or flight data set, varying airport states and capacities, and winds are unique for each day to be simulated. Real world data sources for the flight data set and airport states and capacities require a degree of preprocessing before using them in ACES. This section discusses ACES input data requirements and the real world data sources and preprocessing required to prepare them. It should be kept in mind that real world data quality can itself be questionable making validation using such data difficult.

A. Flight Data Set

An ACES flight data set (FDS) is a set of flight plans including origin and destination airports, scheduled departure time, aircraft type, proposed cruise speed and altitude, and trajectory way points. ASDI is an excellent real world source for this data. ASDI is a subsystem of the Enhanced Traffic Management System distributed as a text feed of raw NAS messages so no text decoding is required. NAS messages are detailed messages about the flight plan, flight plan amendments, departure, trajectory tracking, boundary crossings, arrival, or cancellation. Collectively ASDI NAS messages provide all the information needed to create a flight data set for ACES.

Some ASDI information may need manipulation or combining with other source data to be used as ACES inputs. ASDI routes are delivered as a series of fixes and jet ways[7] and ACES uses way point trajectories. Fix and jet way locations[8–10] are used to convert the last given route before takeoff to a series of latitude/longitude way points. Anticipating using BTS delay statistics for validation, flights extracted from ASDI may be paired and synchronized with BTS flights. When ASDI scheduled departure time varies from BTS scheduled departure time, the BTS time is used. Any BTS flight that is not paired with an ASDI flight may also be added to the data set. BTS data only provides the flight ID, origin and destination airports, and scheduled departure time required for the flight plan. Remaining flight plan information may be extrapolated using flights with similar airport pairs and airlines as guides.

Febuary 19, 2004 was chosen for simulation. It was a high traffic and fair weather day. A total of 56850 flights were extracted from ASDI and BTS for Febuary 19, 2004. Only 3% of the flights required some extrapolation to complete the flight plan. ACES configuration filters some flights for various reasons. ACES's international flight capability is currently limited to flights either originating or terminating within domestic airspace. International overflights are filtered. The airport model used in this validation has a generic circular Terminal Radar Approach Control (TRACON) with 40 mile radius. The origin and destination airport of a flight may not have intersecting TRACONs. Therefore, each origin destination airport pair must be at least 80 miles apart. Overflights and intersecting TRACON flights consist of 16% of the original data set. Another 2.6% are filtered due to ACES identified trajectory anomalies. The total number of simulated flights is 46243, a subset of the original 56850.

B. Airport States and Capacities

Adverse weather conditions are not directly modelled in ACES but the effects of weather on airport capacity can be modelled to a certain degree with airport states. Different airport capacities are used for visual flight rules (VFR) when visibility-distance and ceiling-altitudes are good and instrument flight rules (IFR) when adverse weather reduces ceiling and visibility. Airport capacity refers to the maximum number of takeoffs, landings, and total operations an airport is able to handle. The total operations capacity is usually less than the sum of the takeoff and landing capacities creating a Pareto curve of feasible takeoff and arrival rates.

ASPM provides airport demand, actual throughput, operation rates and state (VFR or IFR) with quarter hour resolution for the top 53 continental US airports. The actual departure and arrival rates may be used as maximum capacity values with total operations equalling the sum of arrivals and departures. This would force ACES to use the exact operations rates per quarter hour reported by ASPM. However, airport throughput is often higher than the reported operational rate during peak efficiency periods. Figure 2 shows ASPM published departure statistics for Fort Lauderdale International Airport (KFLL) on 2/19/2004. Notice how the reported departure rate is more a reflection of average throughput than the actual departure rate the airport performs. ACES treats airport capacities as hard maximums. Peak throughput periods would not be modeled properly if reported operation rates were used. To model the most realistic throughput, these peak maximums may be used as ACES maximum operations capacities. Using maximum hourly throughput rates instead of quarter hourly throughput rates removes especially high throughput rates that cannot be sustained for more than a quarter hour. The hourly average departures for KFLL are shown in figure 2 for comparison with the quarter hourly departures.

The curve in the Pareto curve is maintained by collecting maximum departure, arrival, and total throughput rates separately. The sum of departure and arrival capacities may be greater than the total capacity. Thus, ACES Traffic Flow Management (TFM) agents are free to alter the airport operation mode between departures and arrivals as the flight schedule demands. Figure 3(a) shows the hourly actual departures, arrivals, and total operations throuput rates for one day at KFLL. Each operation maximum may not occur over the same hour. Therefore, even though at any one hour, the total operations throughput may equal the sum of departures and arrivals, the maximum total operations may be less than the sum of the maximum departures and arrivals per hour. Figure 3(b) shows the resulting Pareto curve for this example. The maximum hourly throughput rates used in this validation were collected between 2/12/2004 and 2/26/2004. Throughput rates were also collected separately for VFR and IFR airport states. If any airports VFR throughput is lower than its IFR throughput, the VFR capacity is raised to at least equal the IFR maximum capacity.

Using maximum throughput rates as airport capacities allows ACES' conservative airport Traffic Flow

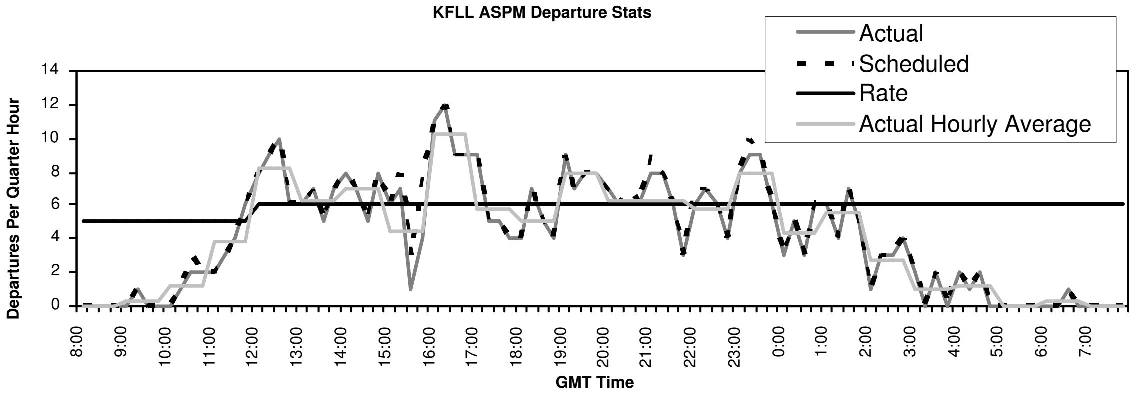


Figure 2. ASPM published departure statistics for airport KFLL.

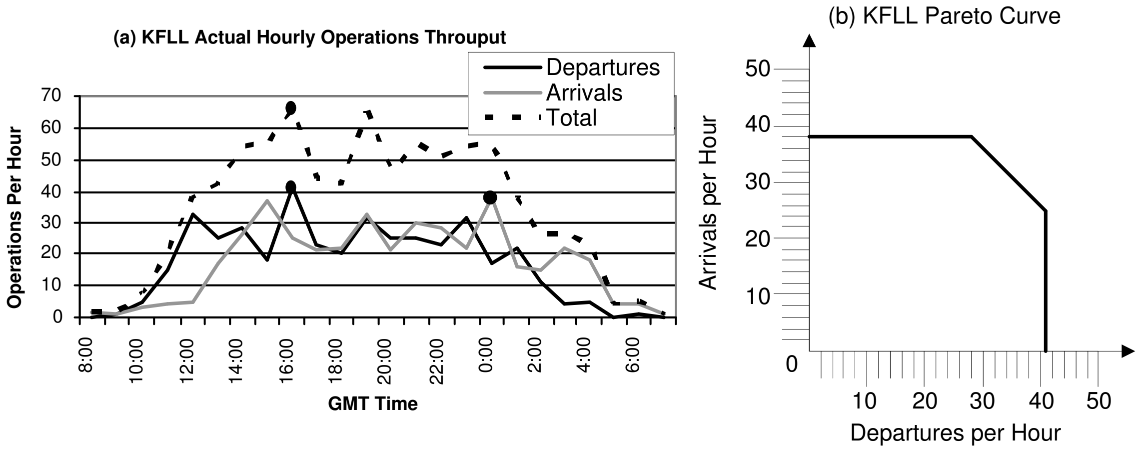


Figure 3. (a) ASPM published actual departures, arrivals, and total operations per hour for KFLL. Maximums for this day are marked with large dots. (b) The Pareto curve produced when using hourly operation throughput maximums from (a).

Management model to simulate realistic throughput levels at the top 53 continental U.S. ASPM provided airports. The remaining airports are given generic airport state capacities based on similar runway configurations. Smaller airports usually have less difference between VFR and IFR capacities and it is less likely for a current day demand size to exceed their capacities. Therefore, all airports other than ASPM are considered to be in VFR state all day. Choosing a good weather day like 2/19/2004 increases the likelihood that these airports are actually operating in VFR conditions. A total of 1669 domestic U.S. airports and 160 other airports including international, Alaskan, and Hawaiian airports were simulated as the origin-destination pairs for the 46243 simulated flights.

C. Other ACES Inputs and Parameters

The functionality used for this initial validation includes airport and sector constraints, lateral enroute delay maneuvers, minimum separation at departure meter fix crossings, and winds. Airport and sector capacities constrain the system by capping airport operation throughput rates and sector densities. These constraints drive the delay in the system which may occur at the departure gate, airport taxi surfaces, TRACON, and enroute airspace. Lateral delay maneuvers allow throughput constraints at the airports and sectors to propagate through the enroute airspace. Departure meter fix separation ensures that aircraft adhere to minimum separation requirements as they transition from the TRACON to enroute airspace.

Environmental conditions in the NAS are highly dynamic and fluctuate throughout the day. Winds affect to a certain degree the routes proposed for each flight as well as the estimated enroute time. Rapid Update Cycle (RUC) data[11] provides information about en-route winds and is used as a direct input to ACES. The winds are then used in ACES to produce realistic ground speeds given a flights desired cruising airspeed.

ACES is capable of addition functionality such as conflict detection and resolution, airline operations control, rerouting, and enhanced terminal area models. These were not utilized in this validation for simplicity.

III. Validation Results

This sections discusses the various comparisons made with the available real world data. First airport throughput comparisons were made using ASPM data. Then BTS delay and flight times were compared to their ACES counterparts. Finally, ACES aircraft state data was compared with ASDI individual flight tracks.

A. Airport Throughput Comparisons Using ASPM Data

ACES collects the time of various stages of flight for each simulated flight which can be used to calculate transit time and delay. Both scheduled and actual times for gate departure, takeoff, departure and arrival meter fix crossing, landing, and gate arrival are captured accurate to the second. Figure 4 shows a diagram of these flight times and how the transit times between them are defined.

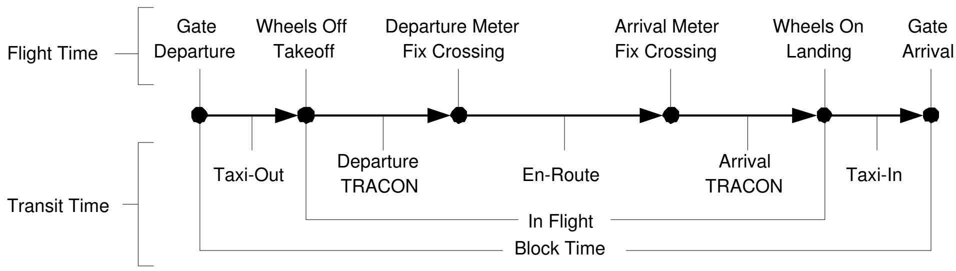


Figure 4. Flight time and transit time definitions.

ASPM publishes flight sums at each of its 53 continental US airports for metrics defined as departure and arrival demands, and actual departures and arrivals per quarter hour. The actual departures and arrivals are equivalent to wheels off and on or actual ACES takeoffs and landings as defined in figure 4. ASPM departure and arrival demands are similar but not quite equivalent to scheduled ACES takeoffs and landings. ASPM counts a scheduled operation any time between it's scheduled and actual wheels off or on time. Therefore, flights with taxi-out delay may be counted for more than one departure demand quarter hour and flights with enroute delay may be counted for more than one arrival demand quarter hour. This is not a true measure of scheduled throughput because the metric is affected by delay which will be compared separately. Figure 5 shows total quarter hourly scheduled and actual takeoffs and landings for the 53 continental US ASPM airports from ACES output data and ASPM. For both takeoffs and landings, ASPM demands are higher than the actual throughput rates illustrating how system delays affect the demand metric. ACES scheduled and actual operations are much closer together. Departure delays cause the actual takeoffs curve to be smoother than the scheduled takeoffs curve. ACES correlation with ASPM varies from 99.1% to 99.6% between scheduled and actual takeoffs. Both scheduled and actual ACES landings correlate 98.3% with ASPM. ACES succeeded in representing 97.9% of ASPMs takeoffs and 92.6% of ASPMs arrivals within the 24 hour period. Individual airport correlations ranged from 73.8% (KBUR) to 97.6% (KDFW) averaging 91.1% for actual takeoffs, and they ranged from 65.4% (KBUR)to 96.6% (KLGA) averaging 84.7% for actual landings. The low correlating airports tended to be lower throughput airports like Burbank, CA (KBUR).

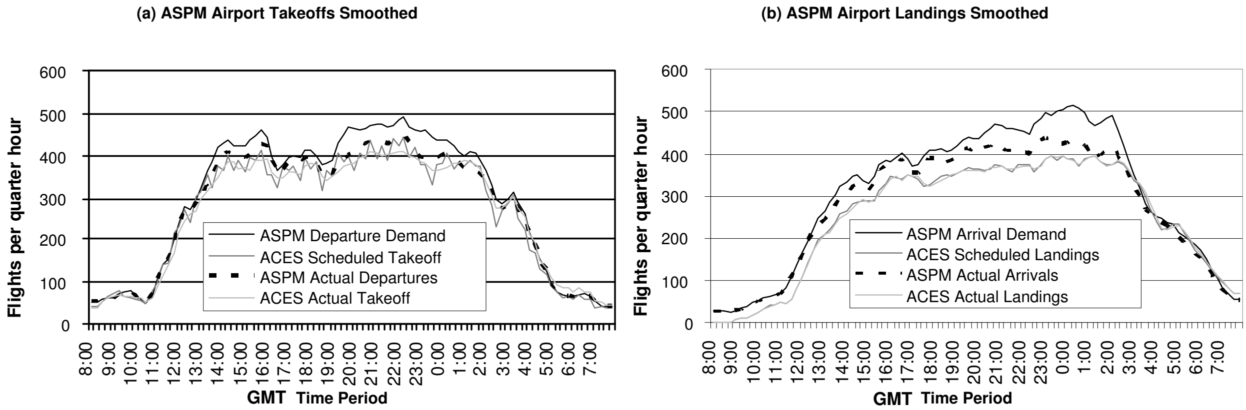
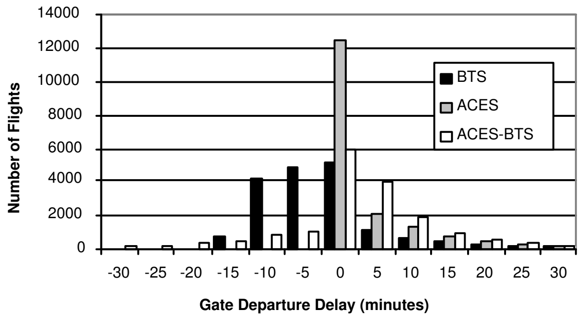


Figure 5. Total continental US ASPM airport takeoffs (a) and landings (b) per quarter hour smoothed by three quarter hours.

B. Flight Time And Delay Comparisons Using BTS Data

BTS provides delay statistics at the individual flight level for certain airlines. It is a much better source for delay and transit time analysis than ASPM summary statistics. Performing summary statistics for all BTS flights and their corresponding subset of ACES flights ensures that the data is comparable and averages will normalize correctly. Due to low fidelity ACES surface modelling and the lack of BTS individual flight unimpeded taxi times, analysis of taxi transit time and delay is moot. More focus is placed on the en-route domain and gate departure delay analysis.

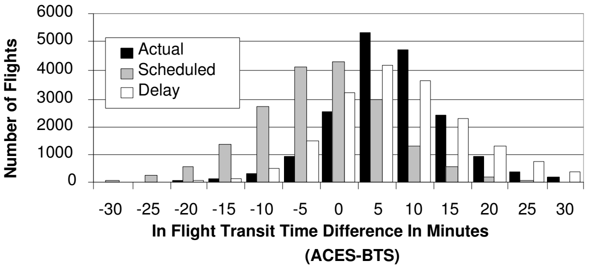


Gate Departure Delay	ACES	BTS	diff
Mean	12.51	2.23	10.28
Standard Deviation	46.46	16.90	49.17
Median	0.97	-1.00	4.20
5% Trimmed Mean	4.85	-0.22	5.44
Min	0.00	-109.00	-315.00
Max	996.50	315.00	970.50

Figure 6. Bar graph of numbers of flights with x amount of gate departure delay accompanied by a chart of summary statistics.

Figure 6 illustrates the gate departure delay analysis and displays gate departure delay summary statistics. Results are skewed by the fact that ACES does not simulate negative delay and over 50% BTS recorded flights for 2/19/2004 departed the gate before the scheduled time. For this reason ACES has 2.4 times as many flights with no delay. It is apparent from comparing numbers of flights with positive delay that ACES overestimates gate departure delay. High delay ACES outliers make a large impact on the mean delay difference of 10.28 minutes per flight. Trimming the sample set by 5% reduceds the mean to 5.44 minutes per flight. The distribution of individual flight delay difference between BTS and ACES around this mean can be seen in figure 6's bar graph.

BTS does not include meter fix crossing times, nor may the real meter fixes be the same distance from the airport as generic ACES meter fixes. Therefore en-route analysis was done using in-flight transit times and delays as specified in figure 4. Figure 7 displays the differences between ACES and BTS in-flight transit time and delay. With a mean difference of 0.16 minutes per flight, ACES is an excellent modeler of mean scheduled in-flight transit time. ACES overestimates actual in-flight transit time and therefore in-flight delay.



Diff (ACES -BTS)	Scheduled	Actual	Delay
Mean	0.16	11.20	11.03
Standard Deviation	9.35	12.45	13.28
Median	0.22	9.97	9.58
5% Trimmed Mean	0.08	10.41	10.32
Min	-44.12	-668.1	-667.9
Max	66.95	203.67	184.53

Figure 7. Bar graph of numbers of ACES flights that differ by x amount with BTS in-flight statistics accompanied by a chart of summary statistics.

On average, BTS actual in-flight transit times are almost 8 minutes shorter than their estimated in-flight time. Section C goes into a more detailed analysis, investigating some possible causes for in-flight differences between BTS and ACES.

C. Individual Flight Trajectory Comparisons Using ASDI Data

ASDI data is used to comparatively analyze a flight trajectory with unrealistically excessive ACES in-flight delay. Figure 8 compares ACES and ASDI trajectories for flight AAL1372 from Chicago to Philadelphia. The ACES in-flight delay is 41 minutes versus BTS's -16.3 minute delay. The flight follows it's filed flight plan at first and then takes a direct-to route. The real world en-route short cut could account for BTS's negative delay but not the excessive delay in ACES.

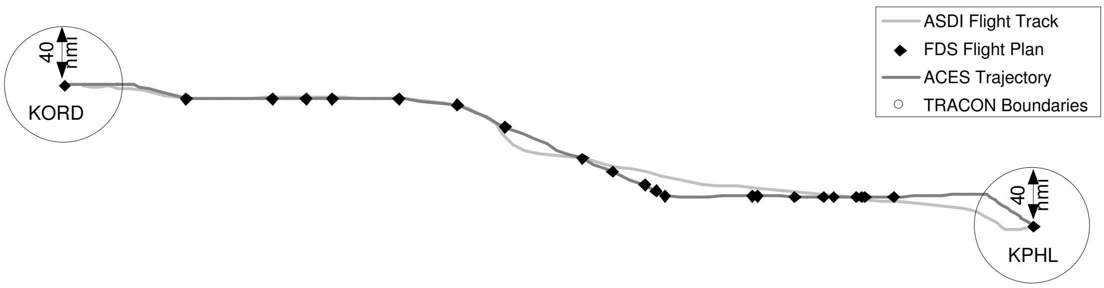


Figure 8. Real world (ASDI) and ACES flown trajectories and flight plan nodes for flight AAL1372 from Chicago O'Hare(KORD) to Philadelphia(KPHL).

In this case the excessive delay in ACES is caused by a unanticipated relationship between the generic nodal airport model and departure meter fix separation functionality. Figure 9 (a) shows ACES's generic nodal airport model in action with just four departure meter fixes at North, South, East, and West and four arrival meter fixes at the corners. ACES assigns to a flight the closest departure meter fix to the flight's first en-route way point and the closest arrival meter fix to it's last en-route way point. This can be seen in figure 8 where the ACES trajectory intersects the airport TRACON boundaries. When using departure meter fix separation functionality, flights may be delayed at the departure meter fix to meet minimum separation requirements before entering the en-route domain. Airports with high departure throughput can result in flights with unrealistic TRACON delay. Figure 9 (b) shows the percent distance completion for flight AAL1372 with respect to time for ASDI and ACES. Departure meter fix separation induced TRACON delay is the source of ACES's 41 minutes of delay. While a small percent of ACES flights have this unrealistic TRACON delay, most of them are KORD departures followed by KDFW departures; two airports with the highest departure throughput rates. For both airports, one or two meter fixes receive the most departures and produce the majority of the TRACON delay. Both the nodal airport model and departure meter fix queueing work exactly as they were designed to. Increasing airport capacity does not increases meter fix capacity, and to avoid meter fix overload more meter fixes must be added, or meter fixes must be placed more strategically to balance departure distribution between the fixes. Current ACES development includes a terminal area model redesign where these insights are being used to establish requirements.

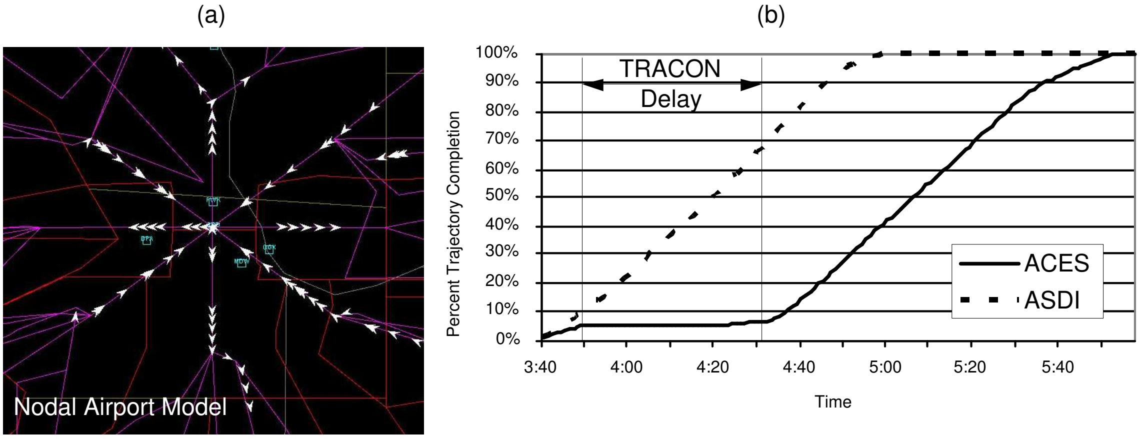


Figure 9. (a) ACES visualization of the nodal airport model implemented at KORD. (b) Percent flight progress for flight AAL1372 with respect to time for ASDI and ACES data.

IV. Summary and Conclusion

This validation proved ACES to be an excellent modeler of the NAS for the level of fidelity utilized. ACES' adequately realistic recreation of current day NAS operations gives greater confidence to future operational concept evaluations using ACES.

The validation produced several note worthy insights that will aid in future ACES development. Realistic traffic levels were achieved by generating flight data sets from ASDI NAS messages and using ASPM maximum hourly throughput rates to drive ACES airport capacities. ACES throughputs correlate with ASPM real world data between 98% and 99%. Delay analysis results show how common negative delay is in the real world. According to delay comparisons, ACES somewhat over estimates gate departure delay and actual in-flight transit time with 5% trimmed mean differences of 5.44 and 10.41 minutes respectively. However, ACES is an excellent modeler of scheduled in flight trajectories with a mean difference less than 10 seconds. Further analysis at the trajectory level, identified real world en-route short cuts and ACES departure meter fix bottlenecks at high throughout airports such as KORD and KDFW as probable causes for in flight transit time overestimation. The departure meter fix bottleneck illustrates how two independently designed models can interact in ways that were not intended.

As these exposed issues are resolved, further validations will aid the development cycle and increase confidence in ACES. Comparisons by region and validations using different weather days will be especially helpful as new methods of implicitly modeled weather are developed.

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