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Modeling Tactical Trajectory Accuracy Effects on Traffic Flow Management Operations

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Software, databases, and methods from previous predictive model studies were used to assess benefits of augmenting parametric methods with kinetic model trajectory predictions. Those results were consistent with other studies of models for aircraft position prediction accuracy during climbs and descents. A kinetic model reduced error for average arrival meter fix crossing time predictions across a one-hour predictive range by 0.6 minutes (39% improvement) when compared to the parametric model used in an experimental traffic flow management system. These results are comparable to the kinetic model's 1.1 minute (47% improvement) error reduction over the operational traffic flow management's parametric implementation. Data also show national convective weather conditions do not appear to affect performance differentials. Kinetic systems do not necessarily ensure performance superior to parametric systems in all areas. Parametric models of air traffic management procedural effects on altitude profiles demonstrated an average 10% error reduction for selected sector entry and occupancy metrics. The sources of these particular errors are not inherent to kinetic methods and could be addressed by procedural modeling improvements. The errors reductions achievable by kinetic models do not ameliorate pre-departure uncertainties, though traffic flow management functions a variety of air traffic management teams and functions may benefit from these levels of increased accuracy at their information exchange boundaries, particularly at Center, sector, and meter-fix crossings.

I. Introduction

THIS paper assesses the performance of two types of deterministic methods used for predicting four-dimensional flight path accuracy and discusses the potential benefits of relevant reductions in error to Traffic Flow Management (TFM) operations. The two deterministic methods used for predicting aircraft trajectories are categorized as either parametric (or kinematic) or kinetic.[1,2,3] Parametric models associate each aircraft with certain climb, cruise, and descent performance parameters, which are typically implemented as table lookup algorithms. A complete trajectory is predicted using climb rate and speed to achieve cruise altitude, cruise speed to capture top of descent, and descent rate and speed to the meter fix. Most predictive systems used for TFM applications employ parametric methods for trajectory prediction. In contrast to parametric methods, the kinetic models associate each aircraft with aerodynamic lift and drag characteristics, and engine thrust, and typically compensate for wind effects. Kinetic models require solutions to the rigid-body equations of motion to predict each aircraft trajectory and are therefore more computationally intensive than parametric methods The traditional motivation for using parametric methods in TFM systems is attributable to computing limitations, but these limitations have been mostly solved by commercial technology improvements. Kinetic models have been recently implemented on high-end multiprocessors to produce multi-center trajectories suitable for TFM operations.[4]

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In a previous study, the authors compared a kinetic model implementation and the TFM operational parametric model performance on several TFM metrics.[5] This study reported that the parametric model implemented in the operational TFM system produced an average absolute error of 2.7 minutes on a TFM arrival meter-fix time. The kinetic model produced an average absolute error of 1.6 minutes, a 39% improvement over the parametric model. This superior performance of kinetic methods is also reflected in the comparison of the kinetic model standard deviation of 2.5 minutes for this metric, compared to 3.5 minutes for the parametric model. Analysis of error in departure aircraft Center boundary crossing-time predictions produced similar results. The kinetic model incurred an average absolute error of 0.9 minute, a 44% improvement over the parametric model's 1.6-minute average absolute error. The kinetic model standard deviation for this Center crossing-time metric was 1.8 minutes, as opposed to the parametric model 2.3 minute standard deviation.

This paper will review the methodology, test-bed models, and databases required to investigate TFM trajectory accuracy issues. The first study assesses the effects of TFM weather conditions on the kinetic and operational parametric model. The second study compares the kinetic model to a novel TFM parametric model that is significantly different from the operational system used in previous studies. The new study indicates that differences in performance are an indication of the two parametric models' efficacy relative to their respective software implementations. In these new studies, the kinetic model demonstrated a 20% difference in performance associated with by sample size differences. Another study documents the kinetic model's 10% greater error rate than the operational parametric method in an important sector occupancy metric. These errors are due to incomplete modeling of current air traffic procedural constraints, such as descent profile operations. The relevance of these results on the traffic flow management domain are discussed, with particular emphasis on benefits to time-based coordination and information flow between different air traffic teams. The impact of relatively small amounts of error reduction for aircraft aloft trajectories is discussed and specific TFM benefits are described. The conclusions call for quantitative explorations of these hypothetical benefits.

II. Background

The organizations responsible for TFM strategic decision making and planning include the System Command Center (FAA SCC), the Airline Operations Centers (AOC), and others who engage in a collaborative decision-making process predicated on reliable and timely exchange of relevant information. These organizations use schedules, flight plans, and predictions of both aircraft and weather to evolve a plan of operation at least 12 hours before each aircraft's expected time of departure. These strategic plans are further analyzed and refined to create a shorter-term strategic plan (1-2 hours before departure) used for coordination between these TFM teams and the Traffic Management Units (TMU) located in Center and Terminal Radar Control (TRACON) facilities. The tactical ATC teams, such as TRACON and Center controllers and their TMU, implement these shorter-term TFM plans in coordination with the aircraft in each controller's assigned sector.[6,7,8]

The effectiveness of the shorter-term TFM plans may be impacted when errors in predicted times for aircraft boundary and fix crossings impair the coordination between different controller teams. For instance, the time each aircraft is predicted to cross its arrival meter-fix is used as coordination data between the Center controller who hands off the aircraft and the TRACON controller who accepts it. This meter-fix arrival time is also used as a basis for coordination between tactical control teams and their local Traffic Management Units (TMU), and by extension to the other TFM teams at the FAA SCC and their collaborative partners.

Many TFM professionals, however, do not accept that more accurate predictions of airborne aircraft position are beneficial to the TFM domain. The largest amount of TFM schedule uncertainty is due to pre-departure factors. The average flight duration is a few hours, and predictive improvements for active en-route aircraft trajectories are typically measured in minutes of reduced error. Pre-departure delay factors may introduce predictive errors measured in hours or even days. Predictive errors for active en-route aircraft therefore necessarily comprise a small fraction of total schedule uncertainty.[9,10,11,12,13]

The TFM realm is therefore principally concerned with aircraft data before they depart, as opposed to aircraft that are already aloft. Many TFM professionals accept that once an aircraft has departed there is little, if any, value on its positional information for TFM operations. Other TFM professionals, however, propose that the TFM domain extends from early planning to each flight's completion at the arrival gate. According to this definition, TFM operates in layers ranging from strategic to tactical.[14]

The latter point of view derives in part from previous investigations on the human factors and inter-facility performance benefits of increasing the accuracy of aircraft arrival meter fix predictions. These studies concluded that the value of predictive accuracy is dependent on location and demand. The tactical benefits of these small

reductions in error have been well documented, particularly in studies of the effects of more accurate crossing time predictions at the hand-off boundary between Center and TRACON controller teams. [15,16,17,18]

Another example of tactical TFM is the operations associated with merging traffic into the overhead stream. More accurate aircraft position predictions could increase coordination efficiency between Center and Tower traffic management controllers.[17,19,20]

The value of these tactical inter-team coordination improvements for TFM remains controversial, insofar as there is a controversy over whether there is any tactical component to TFM. The results section below will illustrate and characterize the comparative performance of kinetic and parametric models. The discussion that follows hypothesizes how the observed improvements in predictive accuracy may benefit TFM operations and inter-team coordination.

III. Methods and Materials

A. TFM Software Systems and Models

Most current systems designed for TFM applications implement parametric models to efficiently process aircraft data covering multiple centers. The FAA's Enhanced Traffic Management System (ETMS), developed by the Volpe Transportation System Laboratory, is a cardinal example.[21,22] ETMS is a core component of the operational FAA TFM system, with networked client processors in every air traffic management facility that includes traffic flow management operations. The Collaborative Routing Coordination Tools (CRCT) developed by MITRE is another TFM software tool that employs parametric predictive models. [23] Studies of the predictive performance of CRCT produced a set of trajectory metrics for traffic flow management applications.[8,9,24] These studies documented that CRCT did not achieve significant predictive accuracy improvement over the operational parametric model in the ETMS. This equivalent performance is attributed to similarities in the parametric methods employed in both systems, though the software was developed separately for each. The Future ATM Concepts Evaluation Tool (FACET) is a novel TFM system developed by NASA for research applications.[25] FACET has its own parametric predictive model implementation. The three systems under consideration: ETMS, CRCT and FACET, originated from different developers with different requirements, though all three systems address common traffic flow management functionalities. Each of these three parametric model systems have a different internal designs and implementations of their respective aircraft prediction software.

The Center TRACON Automation System (CTAS), developed by NASA, employs a kinetic trajectory prediction model.[26] CTAS is an air traffic control tool designed for tactical operations. CTAS uses a sophisticated trajectory synthesis technique that evaluates the physical forces exerted on each aircraft. The relative computational cost of the CTAS method originally restricted its application to single-Center application. CTAS was adapted so that an array of networked processors could acquire ETMS aircraft surveillance data and serve four-dimensional trajectories based on aircraft kinetics for all active aircraft in the Continental United States (CONUS). This configuration of CTAS is called the Traffic Flow Automation System (TFAS).[4] The TFAS implementation is the kinetic model for all the comparative studies described in this report.

One motivation for the current studies is to replicate and verify that previous findings were attributable to differences in parametric and kinetic methods rather than other implementation factors. These other factors could include speed schedule constraints, horizontal or vertical modeling.

Computational test beds were required to calculate four-dimensional trajectories for active aircraft using both kinetic and parametric methods.[27] One of these systems, the Research Traffic Management System (RTMS), was based on the operational FAA ETMS software and hardware. The RTMS embodies the same parametric model implementation as the operational ETMS.

The initial studies were designed to compare the performance of the RTMS parametric model to the TFAS kinetic model, with the objective of increasing operational TFM predictive accuracy, and in so doing improve TFM Decision Support Tool (DST) reliability. The following summary descriptions of the RTMS and TFAS test beds include descriptions of the modifications required to perform the current studies.

B. Research Traffic Management System (RTMS)

The DOT Volpe Transportation Systems Laboratory (Volpe) and NASA Ames Research Center used a wide-area intranet (i.e., secure, encrypted network which was physically isolated from the internet) ETMS feed to be used for TFM research and development. The RTMS provided the kinematic predictive trajectory data used to represent ETMS performance. The RTMS was implemented at the Volpe Transportation Laboratory in a cluster (or 'string') of computers that were identical to the hardware/software configurations of the operational ETMS strings. The essential difference between the baseline RTMS and an ETMS string was the requirement that RTMS was dedicated

to research and development, and shall not be used in any operational TFM activity. The RTMS was connected to the same real-time air traffic control systems data feeds (e.g., flight plans, aircraft states, weather, TFM tools) as the operational ETMS. These data were routinely sent to the NASA systems from Volpe via a secure dedicated high-speed intranet connection.

One significant advantage of the RTMS server string was that, as a purely research system, it was possible to also modify the source code (which is nominally identical to the operational FAA ETMS) to efficiently acquire detailed information on the results of RTMS predictive reliability and accuracy. Some of these data may be recovered by an ETMS or RTMS remote client workstations' networked database query utilities, but only on a limited basis. These remote database queries are computationally expensive and may adversely affect the performance of the ETMS core functions. The RTMS server string (as opposed to the remote clients) was specifically modified to provide predictive trajectory data for all aircraft covered by the system including all aircraft flying within the 20 CONUS Centers. This was achieved by developing new functionalities within the server, rather than on the ETMS clients. The RTMS design for acquiring system-wide data increased the overall computational load by less than 5%, even under peak conditions (~5000 aircraft in 20 Centers).[28] See Fig. 1 for a conceptual diagram of the RTMS.
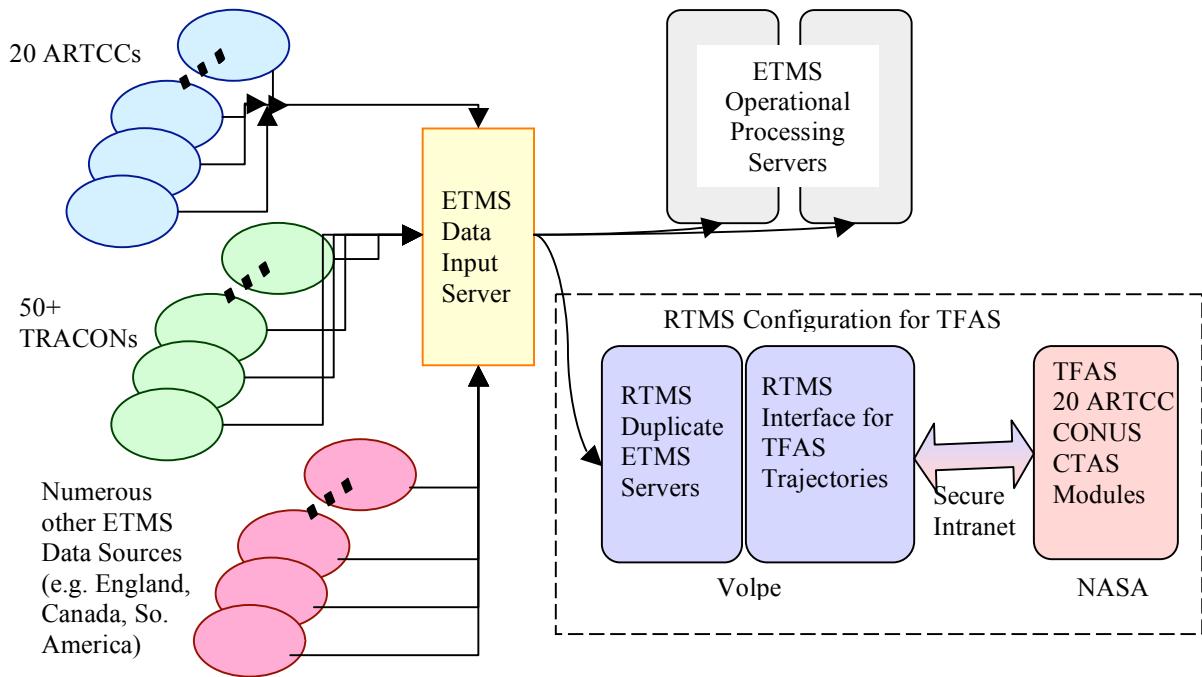

Figure 1. Conceptual diagram of the Research Traffic Management System.

C. Traffic Flow Automation System (TFAS)

CTAS was designed for operation at a single Center. TFAS is a multiprocessor adaptation of CTAS software that is capable of processing trajectories for all air traffic in all 20 of the CONUS Centers. The TFAS architecture re-used the NASA CTAS code baseline, particularly the kinetic four-dimensional trajectory synthesis and route analysis. The FAA currently employs these same algorithms in the operational Traffic Management Advisor (TMA) tool. The performance of the CTAS kinetic model implemented in TFAS is therefore directly comparable to the trajectory synthesis methods used in the current FAA TMA to support Center sector control operations.

Each TFAS server is composed of 20 separate CTAS modules. Each of these modules is adapted for one of the 20 Air Route Traffic Control Centers. The CTAS modules use kinetic methods to calculate each Center's aircraft trajectories, which then become components of multi-Center trajectories for all CONUS aircraft. The 20 CTAS modules are typically co-located in a server configuration. This server may be queried for aircraft trajectory information.[4,5]

D. Future ATM Concepts Evaluation Tool (FACET)

FACET employs kinematic methods similar to the operational parametric model, albeit more sophisticated, to predict aircraft trajectories. FACET was not designed to record detailed trajectory prediction histories but was developed to create trajectory output files for each one-minute ETMS input data file. These output files from both the parametric and kinetic model contain comparably formatted trajectories generated for each aircraft based on the input data messages. Each aircraft trajectory record contains the predicted location (lat, long, alt) at the current position and each subsequent minute. Both the kinetic and parametric models used archived ETMS data as aircraft data inputs. These data come in the form of an ASCII version of the Aircraft Situational Display to Industry (ASDI) feeds.

FACET used the output of the kinetic model to reduce prediction error. These features were developed specifically for this study and are not part of the normal FACET runtime environment.

E. Air Traffic Metrics and Databases

One of the primary questions that this study sought to answer was whether a kinetic model (TFAS) could significantly benefit the predictive performance of a novel parametric model (FACET).[29] The metric selected for evaluating performance was the reduction of error for meter-fix crossing time prediction.[5,15,24] A meter fix is typically a point at which arriving flights are handed off from the ARTCC to the TRACON. The metric is defined as the difference between the predicted and actual meter fix crossing times:

$$\varepsilon_{meterfix} = t_{predicted.cross} - t_{actual.cross} \qquad (1)$$

Acquisition of the '$t_{prediced.cross}$' term requires that each predictive model produce records of aircraft trajectories that may later be compared to the '$t_{actual.cross}$' term. Previous studies required development of data-acquisition software for the operational parametric model server so that its predictive trajectories could be efficiently collected for all aircraft in the CONUS.[28]

The input data used by all the systems (both kinetic and parametric) originated as ETMS data. These positional data are a sample of Center surveillance system. The Center radar data have a sweep-rate of 12 seconds. The ETMS acquires its positional data from a software patch in each Center's Host computer. This patch sends data every minute, at every fifth sweep. The low update rate of the ETMS data can create sampling errors when attempting to use these data to confirm at the actual time an aircraft crosses a fix. Accordingly, determining the '$t_{actual.cross}$' (actual fix-crossing time) requires the higher update-rate of the Center system data to determine the actual (or observed) positions of aircraft. The data requirements therefore include ETMS system data for input, detailed records of predictive model performance, and Center surveillance systems data to establish actual reference values required to evaluate prediction errors. The diversity of the sample size is therefore limited by the availability of Center data.

In previous TFM performance studies the operational parametric model predictions were gathered in conjunction with data from up to twelve different Centers. Table 1 lists the Centers that were used in the studies and the total number of sample days for each. Data were collected from 310 separate 24-hour samples from among twelve different Centers, collected during a three-month period. A comprehensive list of Centers, dates, and the total number of minutes issued by the TFM Ground Delay Program for each sample is described in Appendix 1. Data sampling techniques used to create and validate this database have been documented in previous studies.[5] This database is available upon request to qualified researchers for comparative studies.

Table 1. Centers Represented by Large Reference Data Sample.

Center	ZBW	ZDC	ZDV	ZFW	ZHU	ZLA	ZMA	ZMP	ZNY	ZOA	ZOB	ZTL	Total
Number of Samples	16	27	36	34	2	30	27	28	30	26	22	32	310

This large database of Center data has been used to provide information on the performance of the operational parametric model and on kinetic model performance over an unusually large and diverse sample. It was not feasible to use the large 310 Center-Day sample for the comparative study with FACET due to software development issues. The current comparative study with FACET was accomplished with a substantial, though smaller sample size. The

new database includes detailed trajectory records from both models, along with actual aircraft flight plan and track data collected over four 24-hour periods from four Centers listed in Table 2.

Table 2. Centers Represented in Data Sample for Novel TFM Study.

Center	ZOB	ZTL	ZDV	ZFW	Total
Number of Samples	4	4	4	4	16

These two data samples are identified below as the '310 Center-Day' sample and the '16 Center-Day sample.' A 'Center-Day' in this context refers to the sample of data collected over a 24-hour period from a single Center.

IV. Results

A. Predictive Performance and Ground Delay Conditions

One aspect of potential kinetic model benefits to TFM tasks is the proposition that the effective value of predictive reliability increases when the National Airspace System becomes overloaded and/or is affected by adverse weather conditions. It is beyond the scope of this report to correlate total NAS GDP minutes of delay with quantitative characterizations of weather effects on air traffic management. A 24-hour period with a low number of GDP minutes is qualitatively characterized as a 'good' TFM day, whereas a day with a comparatively large number of GDP minutes is a 'bad' TFM day. The table in the Appendix includes a column for the total number of NAS GDP minutes incurred in each 24-hour period.

National Airspace System Ground Delay Program Minutes Allocated for Each 24-Hour Data Sample
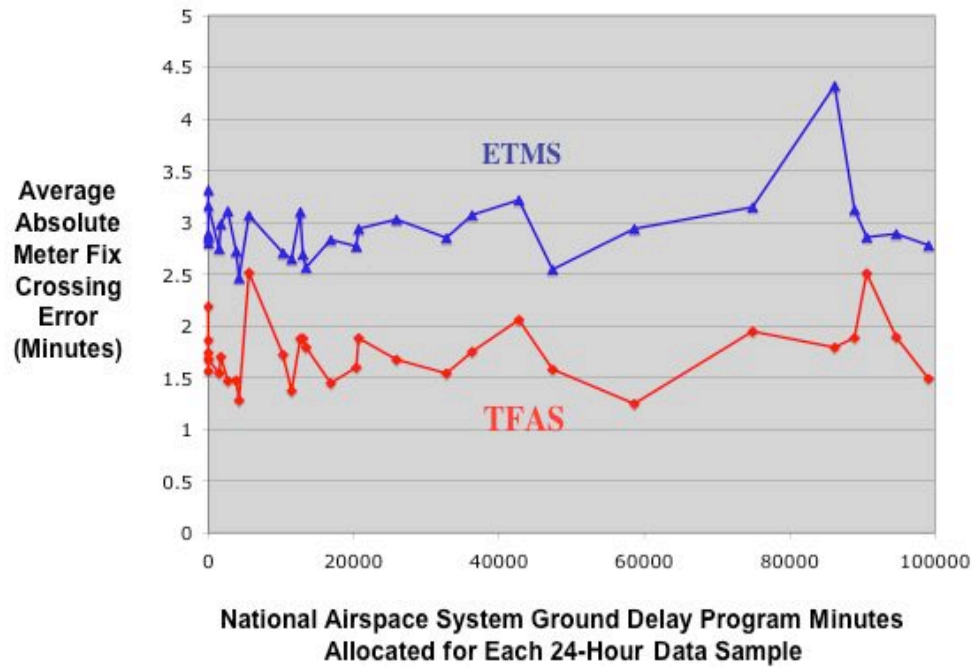
Figure 2. Comparison of TFAS (in red) vs. ETMS (in blue) Performance indexed by number of Ground Delay Program (GDP) minutes in each 24-hour sample. The kinetic system (TFAS) is consistently more accurate, regardless of GDP condition.

Aggregate results from the large (310 Center-Day) sample were grouped by date of collection and ordered by magnitude of GDP minutes for each 24-hour period. The results, terms of average of the absolute magnitudes of the prediction errors, are illustrated in Fig. 2. The kinetic model consistently demonstrated lower errors than the operational parametric model, except for a single 24-hour period in which they were essentially equal.

B. Kinetic and Parametric Model Performance Comparison

A previous NASA study demonstrated a kinetic methods system (TFAS) achieves a 47% reduction of error of 1.1 min. for arrival meter fix prediction. One motivation for performing this study with a novel TFM parametric model was to verify that the differences in predictive performance were attributable to parametric and kinetic methods rather than other implementation factors. These other factors could include speed schedule constraints, horizontal or vertical modeling. The follow-up study used FACET, since it was also a TFM tool that used parametric methods similar to ETMS and CRCT to predict aircraft trajectories. A method was developed to augment native FACET trajectories with TFAS-generated predictions of each aircraft's descent to meter-fix phase of flight. In this method the TFAS predictions replaced the FACET predictions for the descent phase of flight in each aircraft's trajectory. [29]
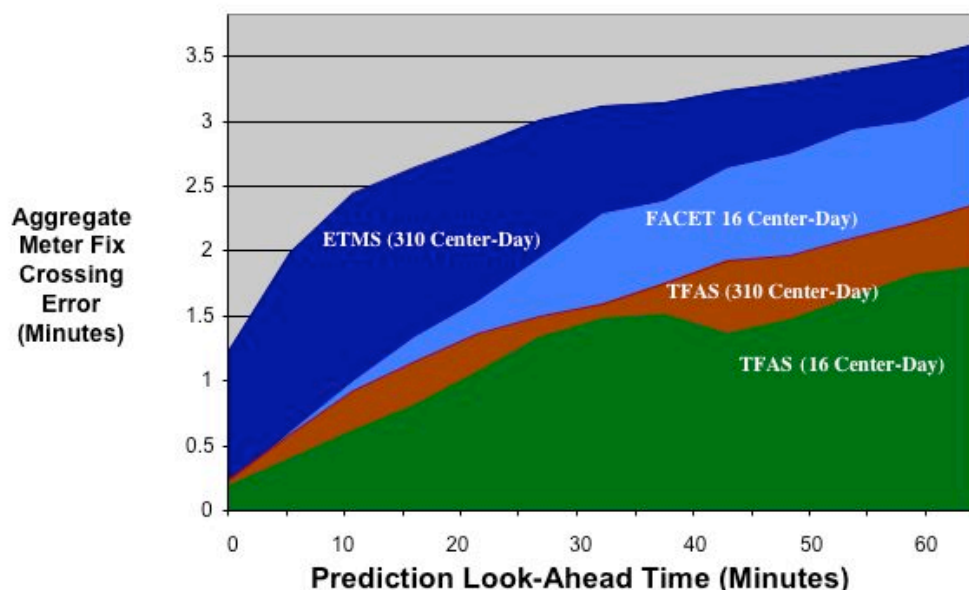

Figure 3. Comparison of Average Absolute Meter Fix Prediction Errors for ETMS, FACET, and TFAS.

A study was performed using 24-hour samples taken over a four-day period from four Centers: Cleveland, Denver, Dallas-Ft Worth, and Atlanta. Fig. 3 illustrates the resultant comparison of these models' averages of absolute fix crossing error. The standard deviations for these averages of absolute error are presented in Fig. 4. The performance of ETMS and TFAS with the larger 310 Center-Day sample is provided for comparative reference.

The results indicate a similar range of error-reduction performance for FACET and ETMS. This is consistent with previous reports of comparable performance for CRCT and ETMS.[8,9] In Fig. 3, the average kinetic model error-reduction performance using the small 16 Center-Day database is shaded in green. The same kinetic model performed 23% better on average and 18% better on the 55-60 min. look-ahead time metric with the 16 Center-Day sample than with the larger 310 Center-Day sample. The area shaded red represents the difference between the same kinetic model's (TFAS) performance on the two samples. The ~20% performance difference is attributable to the broader breadth and depth of the larger sample. Most Centers in the 310 Center-Day sample benefited from the kinetic model, though not all. The performance of the kinetic model for certain Centers that employed a higher than average amount of procedural constraints could actually be worse than the operational parametric model (see section C., below). The 16 Center-Day sample did not include such Centers. The variability may therefore be attributed to sample size and coverage differences.
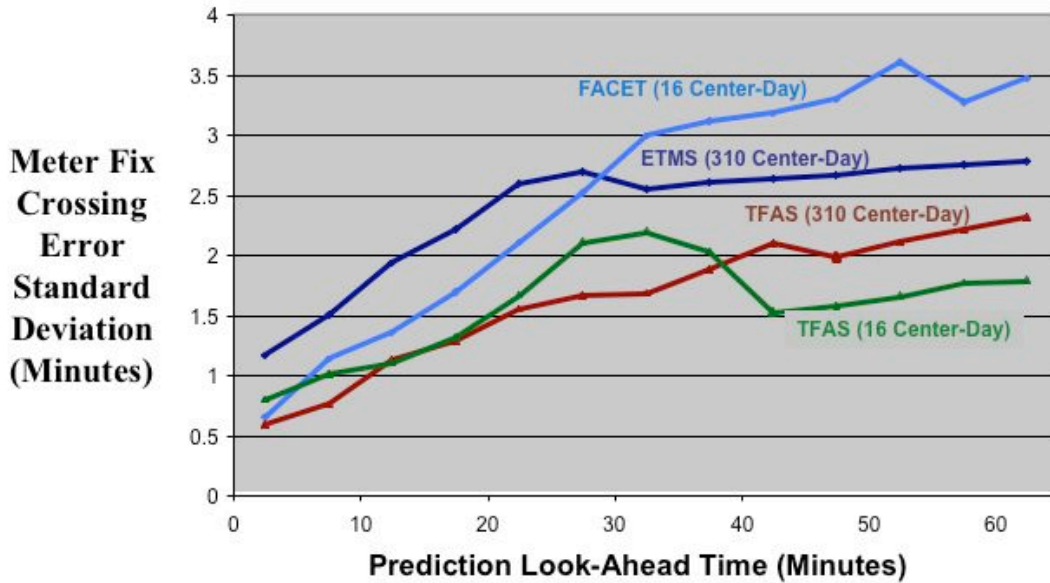
Figure 4. Comparison of Standard Deviations of Average Absolute Meter Fix Prediction Errors for ETMS, FACET, and TFAS.

The kinetic model reduced prediction errors 40% more effectively than the novel parametric model. In this study, both models used identical small 16 Center-Day samples. The combined red and light-blue shaded areas represent the performance difference between the parametric methods and the kinetic model. The novel parametric model performed significantly better for near-term predictions than the operational kinetic model. The dark blue area describes the difference of FACET performance using the small 16 Center-Day sample and the ETMS performance using the large 310 Center-Day sample.

Average absolute errors within 55-60 minute period and average differences in model error reduction performance for this metric are listed in the second row of table 3. The errors and reductions from predictions made 55-60 minutes before the actual meter fix crossing time are listed in the third row. In comparisons with the operational parametric model, the kinetic model reduced error for the one-hour cumulative average arrival meter fix metric by 1.1 minutes, which is equivalent to a 48% improvement. The kinetic model outperformed the operational parametric model on the 60-minute look-ahead prediction metric by 1.2 minutes, equivalent to a 36% improvement. Similarly, in comparisons with the novel parametric model, the kinetic model reduced the average absolute error by 0.6 minutes, equivalent to a 40% improvement, and reduced the 60-minute look-ahead prediction error by 1.0 minutes, equivalent to a 39% improvement. The novel parametric model (using the 16 Center-Day sample) performed 33% better than ETMS (using the 310 Center-Day sample) the one-hour cumulative error metric. Most of these improvements were registered for look-ahead times periods of less than 45 minutes. The novel and operational parametric model errors were equivalent for the 55-60 minute look-ahead time metric.

Table 3: Comparative Meter Fix Crossing Time Prediction Errors (in minutes)

	ETMS [1] Error	TFAS [1] Error	TFAS – ETMS[1] Error Reduction	FACET [2] Error	TFAS [2] Error	FACET-TFAS[2] Error Reduction
Average Meter Fix[*]	2.4	1.3	1.1	1.6	1.0	0.6
55-60 min Meter Fix[**]	3.2	2.0	1.2	2.7	1.7	1.0

Table 4: Comparative Error Reduction Performance of Kinetic and Parametric Models

Model and Sample Comparison	Average Reduced Error (Min)*	Relative Error Reduction*
ETMS[1] - TFAS[1]	1.1	47%
FACET[2] - TFAS[2]	0.6	40%
ETMS[1] - FACET[2]	0.8	32%
TFAS[1] - TFAS[2]	0.3	23%
FACET[2] - TFAS[1]	0.3	22%

C. Descent Profile Modeling Errors

In at least one metric, the operational parametric model exhibits superior performance in comparison with the kinetic model. The 'Sector hit rate' is a measurement of the fraction of flights predicted to enter a sector that actually do enter the sector.[24] The formal definition of this metric is:

$$R_{hitrate} = \frac{count(actual\_flights \in predicted\_flights)}{count(predicted\_flights)} \cdot 100 \tag{2}$$

As illustrated in Fig. 5, the parametric model performed approximately 10% better than the kinetic model in sector hit rate metrics. One explanation for this observation is that the kinetic model was originally developed as tool to advise controllers to keep aircraft flying at high altitudes and then clear them for fuel-efficient idle-thrust descents. This model does not include algorithms for altitude step-down procedures because its associate decision-support objectives include minimizing such fuel-inefficient operations. In this case the CTAS prescriptive model affects the performance of the predictive model. The kinetic predictive model therefore posits certain aircraft in high altitude sectors at times and locations where contemporary air traffic control practice may clear these aircraft to low altitude sectors. These sorts of discrepancies create a particular kind of error in which kinetic model will often misclassify the sector of an aircraft as 'high' when it will actually be 'low'.

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1 Based on data from 310 Center-Day Sample (see Table 1. and Appendix).

2 Based on data from 16 Center-Day Sample, four 24 hour periods from four Centers (see Table 2.).

* Average of 13 bins of data categorized by Look-Ahead time, ranging from a maximum of 62.5 minutes to 2.5 minutes.

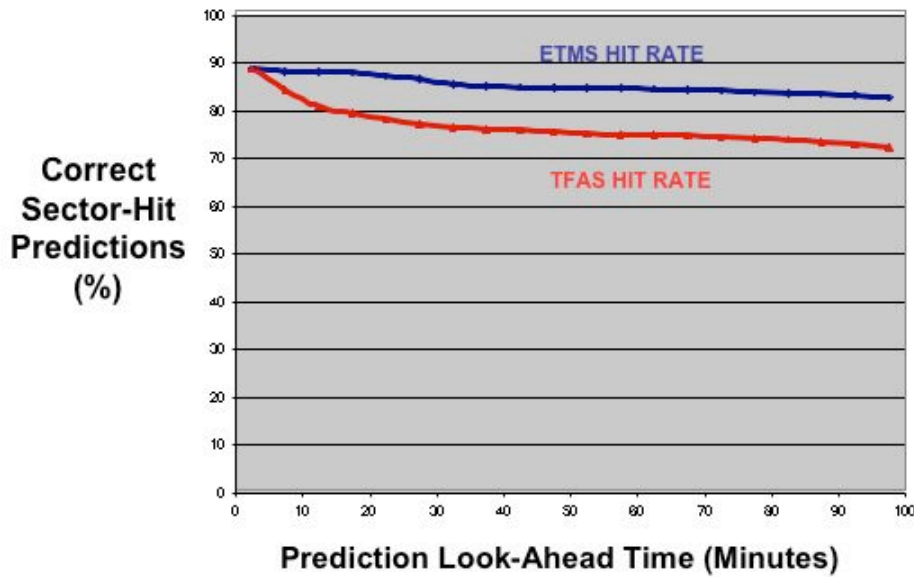** Interpolation of average Meter Fix Crossing Time Error from 57.2 min and 62.5 min look-ahead time bins.

Figure 5. ETMS Achieves better predictive sector hit rate performance than TFAS.

The difference between the prescriptive kinetic prediction and the descriptive parametric prediction cause errors of the sort illustrated in Fig. 6. In this figure the kinetic model vertical trajectory is represented in black. The step-down trajectory is represented in light blue. The aircraft is 'stepped-down' from a high altitude sector to a low altitude sector, though the decision support system functionality had prescribed that it maintains altitude until it reached a 'top-of-descent' point where it could execute a fuel-optimal approach. These results indicate that kinetic methods may achieve superior time-to-waypoint accuracy while simultaneously exhibiting inferior sector-hit rate accuracy in comparison with parametric methods. These errors are attributable to insufficient ATC procedural constraints in the kinetic model implementation, rather than to an inherent flaw in the kinetic model calculations.
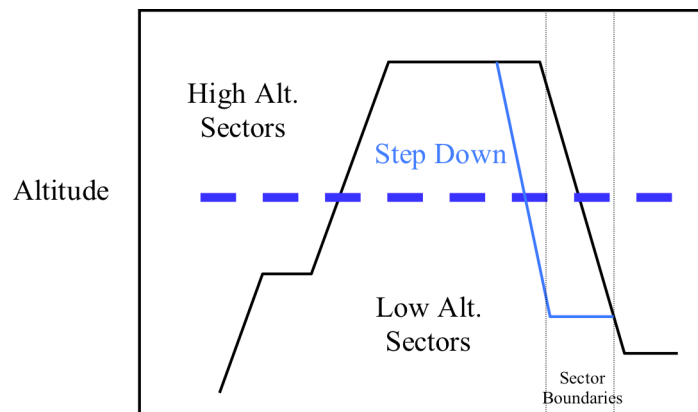

Figure 6. CTAS Sector Hit Rate errors may be attributed to insufficient modeling of ATC altitude profile procedure constraints.

V.   Discussion

I.   TFM Inter-Team Benefits from Predictive Accuracy

Although it is widely recognized that the largest TFM prediction errors are attributable to factors that occur before the aircraft become airborne, the impact of relatively small predictive errors of active (airborne) aircraft may

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have a greater human factors impact on certain ATM processes than the relatively larger pre-flight errors. The explanatory principle for the greater impact of airborne error is that tactical ATC teams are primarily concerned with active aircraft, and when they notice TFM predictive inaccuracies in their own airspace they may then doubt the quality of other information from these same TFM systems. These doubts and associated dissatisfaction may become points of contention between the controller and TMU teams. [30]

A cardinal example of this sort of tactical versus strategic conflict occurs when TFM automation tools generate inaccurate sector monitor-alerts caused by inaccurate sector arrival time predictions. Typically these inter-team conflicts (e.g., TMU vs. Sector Controller) focus on the last 45 minutes of an arrival, when the arrival aircraft are descending (changing altitude) and changing from high to low altitude sectors. Sector controllers cannot judge the accuracy of predictions that concern events outside their airspace, so they may be inclined to base their opinions about TFM automation tools on the accuracy and reliability of the predictions that concern their own sector. When sector controllers observe predictive unreliability, they tend to downgrade the utility of the TFM tools that issued these predictions. This has engendered a number of interesting conversations between sector-controller floor management and the TMU personnel, which often has grown to involve discussions personnel at the SCC and the AOCs. In the past, this has caused certain TMU teams to downgrade the importance of the sector-monitor alert tools in certain airspaces, with attendant system-wide human-factors conflict. [31,32]
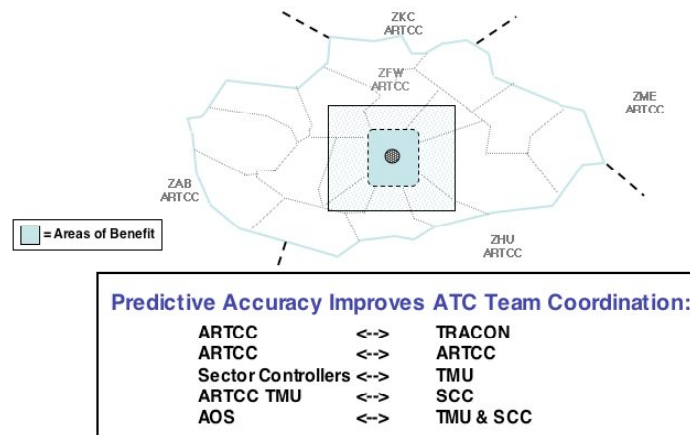

Figure 7. Areas where increased confidence in TFM predictive accuracy may increase inter-team coordination.

These problems may become most noticeable in areas where active aircraft are handed-off between ATC facilities, e.g., at the meter-fixes where ARTCC arrival controllers hand-off aircraft to TRACON, or at coordination-fixes where one ARTCC hands off aircraft to an adjacent Center. Inevitably these mismatches between prediction and actual performance cause a range of system stresses, from mild dissatisfaction to airborne holding and re-routing, that have detrimental effects on a variety of TFM planning activities. The areas where relatively small increases of predictive accuracy may benefit inter-team coordination (using the Ft. Worth Center airspace as a model) are illustrated as in Fig. 7. The following sections discuss potential benefits that may accrue from the reduction in predictive errors that may be realized by employing kinetic rather than parametric models.

II. Arrival Sector Controller – TRACON Coordination

The sequencing of aircraft and the handoff to the TRACON at the arrival fix is difficult. First, the airspace involved is relatively small and frequently adjacent to sectors used for departures. If something does not go as planned, the controller must react quickly and with a full awareness of the aircraft maneuvering in and around the TRACON. The airspace can also be further constrained by weather that affects the either the flow, the capacity region around the meter fix, or the flow at the airport.

The mix of aircraft types affects the sequence of aircraft. The spacing between smaller jets and heavy jets must be larger than between two or more heavy jets. The sequence can affect the use of airport's runways and the arrival rate. Hence, during times when airport arrivals are approaching or exceeding the maximum runway arrival rates, it is

critical that the arrival controller have accurate information. This leads to better sequencing and less uncertainty about the time of the handoff. If predicted arrival rates subsequently turn out to be wrong, however, the arrival controllers may doubt the predictive information from systems they perceive to be unreliable.

III. Adjacent Center-to-Center Coordination

Center-to-center handoffs require the centers to know the times of the boundary crossings. In those cases where the aircraft remain at altitude the current time predictions are sufficiently accurate. However, where the handoff must occur following an ascent or a step down descent the handoff timing will be affected by the sequence and the time predictions. This can result in small delays or it may lead to airborne holding of the aircraft and other significant delays that may impact TFM plans.

IV. Sector Controller – Traffic Management Unit Coordination.

Sector controllers and the TMU implement TFM plans by addressing local issues, such as local weather and other restrictions. Accurate time predictions allow these teams to coordinate more effectively and plan alternatives to minimize delays within their area of responsibility.

Inaccurate predictions require these teams to use resources to address the unpredicted traffic pattern. There is a great deal of anecdotal evidence that this situation creates stress in the workplace leading to a less flexible environment. The controllers and coordinators may become less willing to accommodate irregularities introduced by adjacent teams, often because of the perception of the unreliability of the predictive information.[30]

V. Airline – TMU & SCC Coordination

Departure recovery and other decision support tools require accurate time forecasts to avoid wasting arrival slots. In addition to better in route flight modeling it also requires precise airport management models. Absent these models and data, the only way to account for the uncertainty is to allocate more arrival slots than necessary for the known traffic. In those events where the traffic does not occupy the slots, AOC and ATC communication and coordination have occasionally become negatively impacted. [31]

VI. Merging into the overhead stream

As noted in the Background, merging into the overhead stream is a tactical operation that benefits from the increased accuracy afforded by physics-based methods for climb-out trajectory. The efficiencies and capacities that may be achieved in merging into the overhead stream then accrue to the strategic TFM.[19]

VII. Concluding Remarks

Kinetic methods model climb-out and decent trajectories more accurately than parametric methods. This report replicates and expands on the results of previous comparative studies of the parametric model used in operational TFM systems and a kinetic model. The replication was performed with a novel TFM parametric model that has significant implementation differences from the operational model. In comparisons with both parametric models the kinetic model decreased aircraft along-path behavior errors by approximately one-minute per aircraft altitude transition. Kinetic methods therefore provide approximately one minute of average increased accuracy (with a look-ahead time of one hour) for sector entry time or meter fix crossing time. This performance difference is evident throughout the range of Ground Delay Program conditions, indicating that the kinetic model's relative performance advantage is not adversely affected by severe weather associated with high delay conditions.

The kinetic methods, however, do not always provide advantage; parametric methods perform as well as the more computationally expensive algorithms for most en route flight paths where the aircraft remain on-path and at relatively constant speed. The kinetic methods can actually perform worse than simpler parametric methods, as indicated in prediction of flight path sector-hits. This is particularly evident in cases where profiling modeling errors due to air traffic control step-down procedures are evident. These modeling errors are in not inherent to the kinetic methods, but are artifacts of the original design of the decision support functions implemented in the kinetic model. This could be remedied by adding contemporary air traffic procedural constraint software to the kinetic model. The kinetic model implementation used in these studies was originally developed for prescriptive decision support for fuel optimal descent procedures, so optional logic would be required to make this kinetic model more descriptive of current air traffic behavior. The studies also illustrated the sensitivity of the models to air traffic sample size and composition. The two air traffic databases used in these studies were both large and diverse. Nevertheless, the same kinetic model demonstrated a 20% variability between the two 310 and 16 Center-Day samples.

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The contention that relatively small errors in predicting the position and crossing-times of airborne aircraft may cause a human factors conflict between tactical Air Traffic Management (ATM) and strategic TFM teams remains controversial. The Discussion section suggests operational TFM benefits that may accrue from the reduction of trajectory errors available from kinetic model. Increased predictive accuracy may benefit inter-team coordination for a variety of ATM operations, including meter-fix crossing and coordination-fix hand-offs, sector monitor alert, adjacent controller coordination, Center-to-Center coordination, Center-TRACON coordination, Center-Tower coordination (particularly when merging departures into the overhead stream), controller – TMU coordination, and airline coordination with TMU and SCC. These TFM operational benefits, however, are not unambiguously demonstrated by the results in this or previous studies. Additional studies will be required to model, measure, verify, and validate the benefits of trajectory error-reduction to these ATM and TFM operations.

Appendix
Air Traffic Data Samples

The primary source of data for these analyses came 36 separate days. Data from 12 Centers were collected totaling 310 24-hour data samples. Below is a chart matching particular Centers to sample days. The data sets from each Center that met quality standards for inclusion in the comprehensive studies are indicated by check marks. The column labeled "GDP Mins" lists the total number of Ground Delay Minutes accrued during each sample, reflecting weather conditions during the sample period.

Date	ZBW	ZDC	ZDV	ZFW	ZHU	ZLA	ZMA	ZMP	ZNY	ZOA	ZOB	ZTL	ARTCC SAMPLE	GDP
8/13/2002			✓	✓		✓	✓	✓	✓	✓		✓	8	88938
8/14/2002		✓	✓			✓	✓	✓	✓	✓		✓	8	42732
8/16/2002		✓	✓	✓		✓	✓					✓	6	99118
8/17/2002			✓	✓		✓	✓	✓	✓	✓		✓	8	0
8/18/2002		✓	✓	✓		✓	✓	✓	✓	✓		✓	9	10293
8/19/2002		✓	✓	✓		✓	✓	✓	✓			✓	8	130334
8/20/2002		✓	✓	✓									3	4246
8/21/2002		✓	✓	✓		✓	✓	✓	✓	✓		✓	9	0
8/22/2002			✓	✓			✓	✓		✓		✓	6	74917
8/27/2002		✓	✓	✓		✓	✓	✓	✓			✓	8	5584
8/28/2002			✓	✓		✓	✓	✓			✓	✓	8	0
8/29/2002		✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	10	94677
8/30/2002		✓	✓	✓		✓	✓	✓	✓		✓	✓	9	13451
8/31/2002		✓	✓	✓		✓	✓			✓	✓	✓	8	3844
9/1/2002		✓	✓	✓		✓	✓	✓	✓		✓	✓	9	11467
9/2/2002		✓	✓	✓		✓	✓		✓	✓		✓	8	58607
9/3/2002		✓	✓	✓		✓	✓		✓	✓	✓	✓	9	16872
9/4/2002	✓	✓	✓	✓		✓	✓	✓	✓			✓	9	0
9/6/2002	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓		10	6817
9/7/2002	✓	✓	✓	✓				✓	✓	✓		✓	8	2692
9/8/2002	✓	✓	✓	✓					✓	✓	✓	✓	8	*
9/9/2002	✓	✓	✓	✓				✓	✓	✓	✓	✓	9	0
9/10/2002	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	11	32760
9/11/2002	✓		✓	✓		✓	✓	✓		✓	✓	✓	9	36302
9/12/2002	✓	✓	✓	✓		✓	✓	✓	✓		✓	✓	10	1520
9/13/2002	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	11	20681
9/14/2002	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	11	20359
9/15/2002	✓	✓	✓	✓		✓	✓	✓	✓	✓		✓	10	25887
9/16/2002	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	11	1738
9/17/2002	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	11	12667
9/19/2002	✓	✓	✓	✓		✓	✓		✓	✓	✓	✓	10	90617
9/20/2002	✓		✓	✓		✓		✓	✓	✓	✓	✓	9	47363
9/21/2002		✓	✓	✓		✓		✓	✓	✓	✓	✓	9	0
11/6/2002			✓	✓	✓	✓		✓		✓	✓		7	0
11/8/2002			✓					✓	✓	✓	✓	✓	6	0
11/9/2002	✓		✓	✓	✓	✓			✓		✓		7	0
Samples	16	27	36	34	2	30	27	28	30	26	22	32	310	

Acknowledgments

References

[1] Swierstra, S., Green, S., "Common Trajectory Prediction Capability for Decision Support Tools," *5th USA/Eurocontrol ATM R&D Seminar*, Budapest, Hungary, 2003.

[2] A Nuic, C Poinsot, MG Iagaru, E Gallo, FA Navarro "Advanced Aircraft Performance Modeling for ATM: Enhancements to the BADA Model," *24th Digital Avionics System Conference*, Washington, DC, 2005.

[3] Paglione, M.M., Ryan, H.F., Oaks, R.D., Summerill, J. S., Cale, M.L.," Trajectory Prediction Accuracy Report: User Request Evaluation Tool (URET)/Center-TRACON Automation System (CTAS)," Technical Note ADA365862, FAA William J. Hughes Technical Center, Atlantic City, NJ, 1999.

[4] Murphy, J. R., Reisman, R., Clayton, J., "A Method for Generating Multi-Center Trajectories," AIAA-2002-4764, *AIAA Guidance, Navigation, andControl Conference*, August 2002.

[5] Murphy, J., Reisman, R., Clayton, J., and Wright, R., "Physics-Based and Parametric Trajectory Prediction Performance Comparison for Traffic Flow Management," *AIAA Guidance, Navigation and Control*, Austin, TX, August 2003.

[6] Vranas,P.B., Bertsimas,D.J., Odoni,A.R., "The Multi-Airport Ground-Holding Problem in Air Traffic Control," *Operations Research*, Vol. 42, No. 2, pp. 249-261, 1994.

[7] Bertsimas, D., Patterson,S.S., "The Air Traffic Flow Management Problem with Enroute Capacities," *Operations Research*, Vol. 46, No. 3, pp. 406-422, 1998.

[8] Wambsganss, M., "Collaborative Decision Making Through Dynamic Information Transfer," *Air Traffic Control Quarterly*, 4, pp. 107-123, 1996.

[9] Chatterji, G, Kim, D., Mulfinger, D., Shridar, B., and Sheth, K., "Methods for Establishing Confidence Bounds on Sector Demand Forecasts," *AIAA Guidance, Navigation and Control Conference*, Providence, RI, August, 2004.

[10] Wanke, C., Callaham, M., Greenbaum, D., and Masalonis, A., "Measuring Uncertainty in Airspace Demand Predictions for Traffic Flow Management Applications," *AIAA Guidance, Navigation and Control Conference*, Austin, TX, August 2003.

[11] Wanke, C., Mulgund, S., Greenbaum, D., and Song, L., "Modeling Traffic Prediction Uncertainty for Traffic Management Decision Support," *AIAA Guidance, Navigation and Control Conference*, Providence, RI, August, 2004.

[12] Wanke, C., Zobell, S., and Song, L., "Probabilistic Airspace Congestion Management," *AIAA Aviation, Technology, Integration, and Operations (ATIO) Conference*, Arlington, VA, September, 2005.

[13] Thipphavong, J. and Landry,S., "Effects of the Uncertainty of Departures on Multi-Center Traffic Management Advisor Scheduling," *AIAA 5th Aircraft Technology, Integration, and Operations (ATIO) Conference*, Arlington, Virginia, Sep. 26-28, 2005.

[14] Chambliss, et. al., "Midterm FAA-Airspace Collaborative Routing Operational Concept," MITRE Technical Report MP98 W0000123, MITRE CAASD, McLean, VA, 1998.

[15] Swenson, H. N., Hoang, T., Engelland, S., Vincent, D., Sanders, T., Sanford, B., and Heere, K., "Design and Operational Evaluation of the Traffic Management Advisor at the Fort Worth Air Route Traffic Control Center," *1st USA/Europe Air Traffic Management R&D Seminar*, Saclay, France, June 1997.

[16] Jackson, M.R., Zhao, Y. J, Slattery, R. A., "Sensitiy of Trajectory Prediction in Air Traffic Management," *Journal of Guidance, Control, and Dynamics*, Vol.22, No.2, pp. 219-228, 1999.

[17] Hoang, T., Farley, T., Foster, J., Davis, T., "The Multi-Center TMA System Architecture and Its Impact on Inter-Facility Collaboration," *AIAA Aircraft Technology, Integration, and Operations (ATIO) Conference*, Los Angeles, CA, 2002.

[18] Meyn, L. and Erzberger, H., "Airport Arrival Capacity Benefits Due to Improved Scheduling Accuracy," AIAA Paper AIAA-2005-7376, *AIAA 5th Aviation Technology, Integration and Operations (ATIO) Forum*, Arlington, Virginia, September 2005.

[19] Kopardekar, P., Green, S., and Thompson, P., "Improving Efficiency of Departure Release communications for En Route Overhead Traffic Flow Management," *23rd Digital Avionics Systems Conference*, Salt Lake City, UT, 2004.

[20] Kopardekar, P., Green, S., Brinkman, C., Thompson, Evans, M, and Davis, D., "Making Internal Departure Release Operations More Efficient," *4th Aviation Technology Integration Operations Forum*, Chicago, IL, 2004.

[21] "Enhanced Traffic Management System (ETMS) Functional Description," Version 5.0, Report DTS56-TMS-002, Volpe National Transportation Systems Center, U. S. Department of Transportation,, Cambridge MA, June 1995.

[22] "Enhanced Traffic Management System (ETMS) System Design Document," Version 6.0, Report DTS56-TMS-008, Volpe National Transportation Systems Center, U. S. Department of Transportation, Cambridge MA, March 1999.

[23] Beaton, E. K., L. S. Rhodes, L. R. Rhodes, and R. Robbins, "CRCT Capabilities Detailed Functional Description," MTR 00W302R1, The MITRE Corporation, McLean, VA, November 2002.

[24] Lindsay, K.S., "A methodology and results for comparative assessment of the prediction performance of the Collaborative Routing Coordination Tools(CRCT)," 2003 *AIAA Guidance, Navigation, and Control Conference*, 2003.

[25] Bilimoria, K. D., Sridhar, B., Chatterji, G. B., Sheth, K. S., and Grabbe, S. R., "FACET: Future ATM Concepts Evaluation Tool," *Air Traffic Control Quarterly*, Vol. 9, No. 1, 2001, pp. 1-20.

[26] Erzberger, H., and Nedell, W., "Design of Automated System for Management of Arrival Traffic," NASA, TM 102201, Ames Research Center, June 1989.

[27] Masalonis, A., et. al., "Preliminary Analysis of CRCT Traffic Prediction Performance" The MITRE Corporation, March 2001.

[28] Rosenberg, N., "TFAS FDB Data Logging Function," Volpe National Transportation Systems Center, U. S. Department of Transportation, Cambridge MA, September, 2002.

[29] Murphy, J., Reisman, R., Sheth, K., and Kim, D.,"TFAS<->FACET-SWEPT Integration Demonstration and Analysis," AATT FY03 Milestone 8.900.2 Final Report, NASA Ames Research Center, Moffett Field, CA, October, 2003.

[30] Krolak, P., "Human Factors and Accurate Flight Path Prediction," Volpe National Transportation Systems Center, U. S. Department of Transportation, Cambridge MA, September, 2002.

[31] Krolak, P., "Effects and Benefits of Predictive Accuracy on Air Traffic Management Performance," Volpe National Transportation Systems Center, U. S. Department of Transportation, Cambridge MA, August, 2004.

[32] Murphy,L., Smith,K., Knecht,B., "Four Studies of the Monitor Alert Function of the TSD," , KSU HFRL Report 99-G-020-3, Kansas State University, Manhattan, KS, 1999.