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Improved Trajectory Information for the Future Flight Planning Environment

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Abstract—**The impact on ATM performance of improved trajectory-related information exchange was determined. This was first evaluated on trajectory prediction accuracy with a follow-on impact on conflict detection and resolution and flow management performance. The trajectory prediction model was validated against operational data to ensure validity of the impact of variability in parameters. The distinction between pre- and post-clearance trajectories enabled an assessment of the impact of open versus closes clearances. Uncertainty was shown to be reducible to one-third of present levels with closed clearances and improved data exchange. Normalized conflict detection performance was sensitive to the transitioning state of flights, significantly more than to airspace. Resulting improvements in resolution were shown to reduce conflict-induced perturbations by up to 3.5 nautical miles per flight hour. The combined reduction in uncertainty and conflict-induced perturbations were evaluated against alternative TFM strategies. An example illustrated reductions in fuel of 60 pounds per flight, 2.2 minutes of ground delay and 50 seconds of airborne delay per flight.**

Keywords-trajectory prediction, conflict detection, conflict resolution, flow management, flight planning

I. INTRODUCTION

Migration towards Trajectory-Based Operations (TBO) has been incorporated in future Air Traffic Management (ATM) concepts for the Globe through ICAO [1], the US through NextGen [2] and Europe via SESAR [3]. These concepts rely on an environment in which flight information, including trajectory-related information, is shared among collaborating air and ground systems. The evolution towards this environment is articulated in the ICAO Flight and Flow – Information for a Collaborative Environment (FF-ICE) Concept Document [4] representing the global vision for modernization of the flight planning provisions. At the 12th Air Navigation Conference in November of 2012, the meeting "expressed its full support for the concept and agreed there was a need for all partners to support a single concept of operations using FF-ICE" [5]. An initial step towards realizing this vision involves the development of the Flight Information Exchange Model (FIXM) [6] which is being developed as a standard for replacement of the Flight Plan items defined in the ICAO PANS 4444, Appendix 2 [7]. FIXM is also being incorporated into initial SESAR requirements, "XML/FIXM format shall be used for extended flight plan data exchange" [8].

As the ATM community seeks to determine FIXM information items in support of trajectory-based operations, the performance impact of alternative exchange strategies must be evaluated. This paper investigates the flight efficiency impact of trajectory information exchange through conflict detection and resolution (CD&R) improvement, followed by an example illustrating the flow management performance impact. This performance is evaluated under a set of alternative cases including voice versus data communication and differing TFM strategies.

II. APPROACH

An investigation of trajectory information needs for FIXM was undertaken through fast-time Monte Carlo simulations. This involved a multi-layered approach whereby the impact of trajectory-related information exchange was evaluated on: a) trajectory prediction accuracy, b) conflict detection and resolution, and subsequently c) flow management performance. The results of each step were expressed in terms of key performance indicators (KPI) [9] and system operating characteristics (SOC) [10] which were used as input to the subsequent evaluation step.

In addition to simplifying the complexity of the analysis, the decomposition into discrete steps allows the reporting of interim performance indicators. This provides visibility into the performance mechanism and allows interim data to be used for subsequent analyses.

A. *Trajectory Prediction and Exchange*

Evolution towards the FF-ICE Concept enables the ground-to-ground exchange of consistent and up-to-date trajectory-related information. Higher levels of accuracy can also be achieved by obtaining information from the highest-fidelity source. This includes the exchange of information necessary for a more accurate ground-based trajectory prediction, or the exchange of a trajectory obtained directly from a flight operator.

The exchange of trajectory-related input information has long been recognized as impacting trajectory prediction [11-

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12]. For this analysis, we incorporated the accuracy impact of exchanging the following:

- Aircraft takeoff weight
- Speed schedule including climb, cruise and descent speeds
- Aircraft engine make, model and series
- Climb de-rating
- De-icing settings
- Drag correction
- Turn parameters

Wind forecasting accuracy was assumed at present levels (i.e., Rapid Refresh, 13 km grid) and modeled through a multiple-scale random signal [13]. The effect of large-scale errors in lateral intent as reported in [14] were not assumed to be present as it is expected that automation would have access to route amendments as the FF-ICE Concept becomes reality. However, some lateral uncertainty would remain, post-clearance, depending on how clearances are provided to the flight deck [15]. Vertical constraints are also assumed to be synchronized across systems in an FF-ICE environment.

In the case of trajectories provided by the flight-deck, it is assumed that aircraft automation has access to wind information synchronized with ground automation. In providing a trajectory to the ground, additional errors accrue as a result of trajectory representation dependent on the number and types of waypoints transmitted. It is recognized [16-18] that for the case of aircraft-provided trajectories, a ground-based prediction will still be required for decision support automation to conduct trial planning, or "what-if" analyses.

It is expected that any future flight information exchange will be realized in an environment with mixed capabilities. For this reason, we evaluate the impact of information exchange on trajectory prediction accuracy as a function of the following capability levels:

- No operator exchange of trajectory-related data beyond present-day flight planning capabilities.
- Exchange of trajectory-related parameters through an enhanced and dynamic flight planning process. (Future SC-214 ADS-C messages may also be used, but are not required.)
- Provision of a short-term aircraft-predicted trajectory to ground systems for incorporation into a ground trajectory.
- Provision of closed, unambiguous clearances via CPDLC [15].

Each of the above capabilities will have an associated level of trajectory prediction accuracy dependent upon the input data quality and the operational conditions under which the accuracy is evaluated. The effect of operational condition variability affecting prediction accuracy was incorporated by sampling over 20,000 flights operating under a range of conditions.

One additional consideration for prediction accuracy is whether a trajectory is pre- or post-clearance. Subsequent to a clearance being issued to the flight deck, ambiguity may exist in the execution of the clearance as a result of latency in communication or execution, or lack of precision in the provided instruction. For example: a voice clearance to vector does not provide a closed clearance, a climb "now" to a new flight level does not specify when the maneuver begins, and a climb to reach a flight level by a position does not specify the start of the maneuver. These inaccuracies would be expected to be short-lived as surveillance updates or receipt of an aircraft trajectory would enable re-conformance to the executed trajectory. However, the clearance determined through decision support automation would be based on the predicted trajectory subject to these inaccuracies.

Evaluation of the accuracy impact of the capability levels previously described was conducted for applicable pre- and post-clearance trajectories. The exchange of trajectory-related input data is expected to impact both pre- and post-clearance trajectories. The exchange of an aircraft trajectory is only applicable pre-clearance. The provision of closed, unambiguous clearances through CPDLC applies post-clearance.

Trajectory prediction metrics were determined for each capability and pre-/post-clearance combination in climb, cruise and descent as the covariance matrix in along-track, vertical and lateral prediction error at a fixed look-ahead time of ten or twenty minutes.

B. *Conflict Detection and Resolution*

Using the covariance matrices for the pre-clearance trajectories determined as part of the above analysis, the performance of a conflict detection (CD) function is obtained. The CD performance is expressed as System Operating Characteristics (SOC) describing the trade between False Alerts and Missed Alerts as variable lateral and vertical buffers are imposed.

In general, CD performance will depend on the trajectory prediction accuracy in addition to other factors, most notably:

- Traffic density – increasing the number of flights will increase the number of conflicts more than proportionally, depending on the flow structure (quadratically for random flow). As buffers are imposed, false alerts will grow faster in a dense environment.
- Transition mix – the mix of climbing, cruising and descending traffic impact the level of estimated position inaccuracy in each encounter. This impacts both the false and missed alert rate.
- Flow Conditioning – upstream flow conditioning affects the frequency of in-trail proximity events.
- Traffic mix – speed and climb rate variability within a given airspace affects the probability of conflicts.

The impact of the traffic density and transition mix can be mitigated through normalization of the missed and false alerts with detected conflicts and the reporting of different SOC curves by conflict pair types (e.g., transition/transition, level/level conflicts). This was verified by comparing the curves across differing airspace across the NAS with highly variable densities. These included climb and descent transition airspace in addition to airspace with significant crossing traffic.

The impact of flow conditioning was included by rate-conditioning flights into the airspace used for conflict detection evaluation. This rate-conditioning incorporated variability reflecting delivery accuracy commensurate with the case being investigated. Traffic mix reflected the mix of traffic in the applicable airspace.

Using the SOC curves from conflict detection cases, an operating point was obtained providing lateral and vertical separation buffers for detection [19]. The buffer size was obtained as prediction accuracy improved to maintain a constant missed-alert rate at a ten minute look-ahead horizon. This approach resulted in the total alert rate (correct + false alerts), allowing an estimate of the number of flights to be displaced for resolution. Flights were displaced for resolution using conflict geometries replicating those obtained in the NAS (e.g., [20]). A larger resolution buffer was assigned by maintaining the same missed-alert rate as above on the SOC curves obtained using the post-clearance trajectories. This permitted the development of distribution functions for the trajectory perturbations due to conflict detection and resolution (CD&R) under prediction uncertainty. These were expressed as the resulting time shift probability distribution for each detected conflict event.

C. Flow Management

The relationship of trajectory prediction accuracy to flow management is multi-faceted. As previously described, one role of tactical flow management is to condition the flow thereby reducing the probability of conflicts. The efficacy of this conditioning is affected by the accuracy with which the upstream flow trajectories can be controlled. This pre-conditioning effect was included in the CD SOC curves described previously.

Strategic flow management controls flows such that downstream capacity constraints are not exceeded. Given the long look-ahead horizons, decision-making is based upon uncertain capacity and demand information. In particular, demand is significantly affected by departure time uncertainty and knowledge of flights' existence (i.e. "pop-up" and duplicate flights). Some of this uncertainty is expected to be mitigated through the broader and earlier provision of flight planning information as described in the FF-ICE concept [4]. However, uncertainty will remain with various possible strategies for mitigating the effects:

- Flexible Planning – A plan for meeting constraints is adjusted in response to changes. Uncertainty leads to inefficiencies from the execution of a changing plan (e.g., speed up, then slow down) and from under-utilized capacity.
- Buffers – Plans accommodate expected aggregate biases in demand through capacity buffers and departure uncertainty is mitigated through buffers on departure time. Inefficiencies result from excess departure delays and inaccurate capacity allocation.
- Control – Earlier control to a plan, given a limited speed-control envelope, provides a greater likelihood that flights will make controlled arrival times. However, there is an operational cost to control and not all disturbances can be rejected.

Some combination of these strategies will continue to be required under future operations due to remaining uncertainty. However, the exchange of consistent, more accurate and earlier trajectory information, enabled through the FF-ICE concept, improves the efficacy of these strategies. This paper investigated this effect.

III. MODEL VERIFICATION

As this investigation relied upon fast-time simulated trajectories, their profiles were verified against operational data. The trajectory model used was Eurocontrol's BADA 3.8 model, with supplementary data to enable variation of trajectory input data.

The impact of data exchange on trajectory prediction was modeled by comparing predicted trajectories with perfect information modeled as 'truth" against trajectories with errors in select input parameters described in Section II.A. Having a correct estimate of the variability in the input parameters was essential for determining the trajectory error. Further, no single source verifying the magnitude of input variability could be found. For this reason, the verification of input data variation is described in more detail below.

A. Effects of Input Variation

A model of weight variability was developed considering: variations in load factors, stage length (air-distance), fuel tankering, and belly cargo. When weight is unknown to a ground DST, the DST may reduce this variability by considering the flight's stage length. The ensuing residual error from this model was compared to aircraft weights obtained from operational flight trial data as shown in Fig. 1 for one aircraft type. Other types were also compared with similar results. The figure shows good agreement between the model and the actual flight weight distribution.

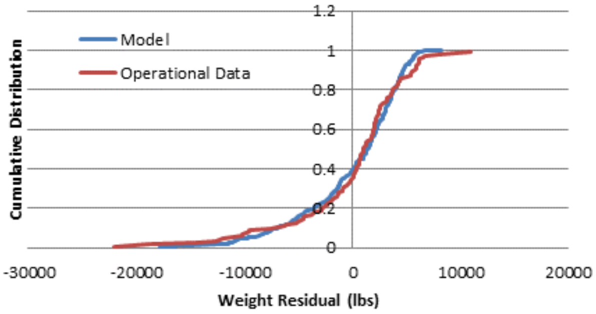

Figure 1 Comparison of residual weight error distribution between model and operational data

A model of wind uncertainty was applied as described in [13] and modified to reflect the accuracy of the rapid refresh. The wind uncertainty model was compared with the error to the forecast using downlinked winds obtained from operational flight trials. The along-track auto-correlation of the wind error agreed as shown in Fig. 2. The rms wind errors obtained from flight data lay between the errors for the 1 hour forecast and analysis as shown in Fig. 3. Differences were expected due to measurement error differences and the fact that the aircraft measurements are not synchronized with the analysis. The simulation used the largest error as input to be conservative.

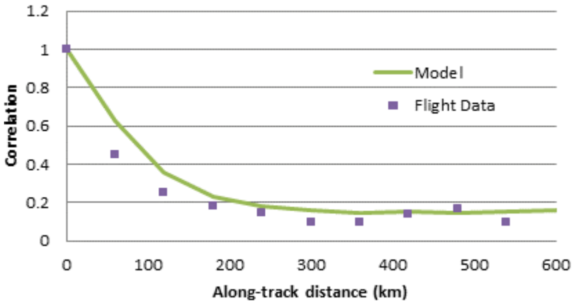

Figure 2 Along-track wind error autocorrelation

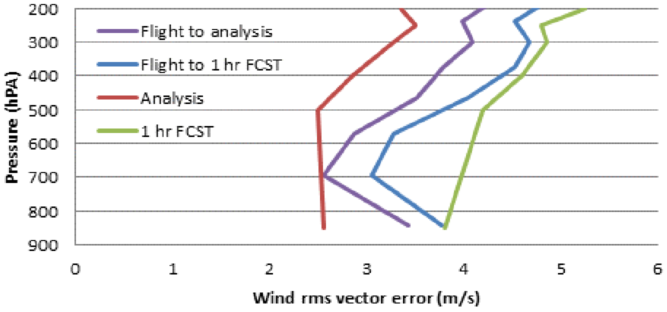

Figure 3 RMS of wind errors to 1 hour forecast and analysis

Cruise, climb and descent speed profile variability was also compared as a function of altitude for multiple aircraft types. Agreement in the mean, inter-quartile range and 95th percentile are as shown in Fig. 4.

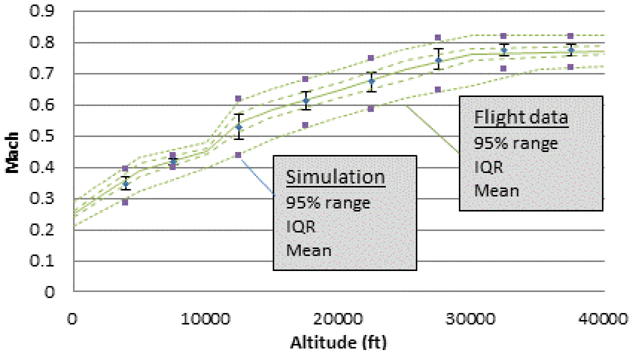

Figure 4 Variation in climb speed as a function of altitude for model and operational data

The impact of de-icing settings on top-of-descent (TOD) location has previously been investigated [21] using data from an FMS test bench. A separate model of thrust variation with de-icing setting was verified against this prior work by replicating the operational conditions and comparing the histogram of TOD movement due to de-icing being turned on (see Fig. 5). The average TOD shift reported from the FMS test bench in [21] was of 5.8 nautical miles. A 5.7 nautical mile shift was obtained using the simulation model herein.

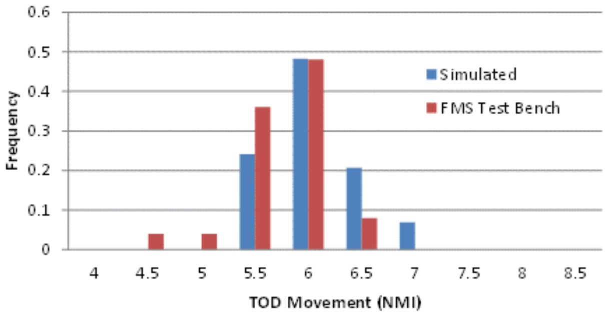

Figure 5 Top-of-descent movement due to de-icing

B. *Overall Trajectory Variability*

Results from verification of individual component effects indicated satisfactory agreement. The components were then combined into a single model of trajectory variability, to determine whether the model captures the same variability and mean as observed in operations. In addition to the components described in the prior section, the effect of aircraft engine series, winglets, small drag profile variations and climb de-rating were incorporated.

Aircraft engine make, model and series were assigned in proportion to data from a weighted combination of known domestic (US) and international airframes. Climb de-rating was applied in proportions similar to that observed in flight trials with logic on minimum climb gradients determining when de-rating could be applied. Drag reductions due to winglets were imposed in proportion to the fraction of winglet-equipped aircraft for a given aircraft series.

Climb gradient simulation data was verified against operational data obtained across a sample of flights for a given aircraft model. Climb gradient mean and standard deviation data is presented in Fig. 6 as a function of altitude. The mean and standard deviation agree as shown.

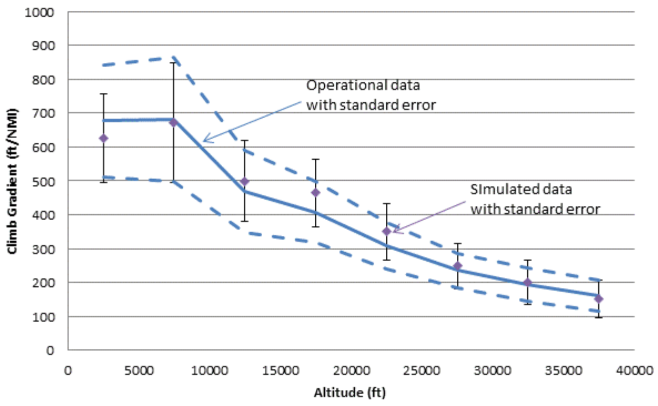

Figure 6 Comparison of simulated climb gradient variation against variation in operational data

IV. PERFORMANCE IMPACT

The trajectory prediction model verified in the prior section was used to investigate the performance impact of differing information sharing capabilities. This performance impact follows a chain of effects from trajectory prediction accuracy through conflict detection and resolution to flow management.

A. Trajectory Prediction

The impact of data exchange on prediction accuracy was investigated by comparing the trajectory prediction accuracy by phase of flight when trajectory input data is known with the best precision available versus assuming a nominal case. Fig. 7 illustrates the impact of the exchange of various factors on the RMS over 21811 flights of each flight's peak altitude error in climb or descent. For example, weight contributes an rms of 1200 feet to the peak altitude rms error.

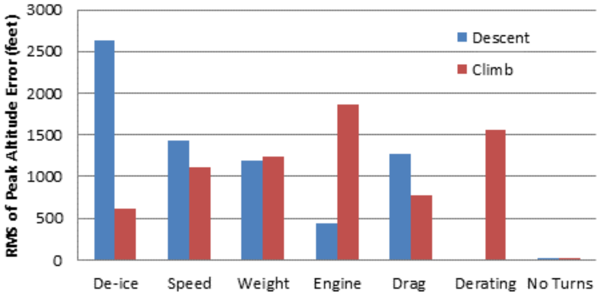

Figure 7 Impact of factors on rms of peak altitude errors in both climb and descent

The de-icing impact appears large as it reflects a specific operational condition in which there is a 50/50 chance of de-icing being required. The impact of a de-rated climb is not relevant in descent. For this case, we assumed a variation of 3% in drag due to the combination of antennae and winglets. The negligence of turns in modeling does not have a significant effect on peak altitude errors. Most other factors have a comparable effect on the peak altitude errors.

A box-and-whiskers plot is shown for the impact on along-track error at a twenty minute look-ahead horizon in Fig. 8. In this case, additional information is exchanged as we move to the right on the chart. As expected, accurate knowledge of airspeed provides the largest single-factor reduction in along-track error.

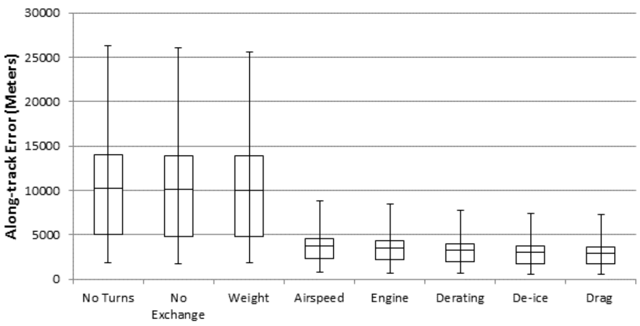

Figure 8 Impact of factors on along-track errors (statistics of flight rms data)

Exchange of the described parameters would be expected to result in prediction accuracy largely driven by the residual wind uncertainty together with variations stemming from flight mode selection and execution.

For the case of an aircraft-derived trajectory, it will have a similar level of residual error due to remaining wind uncertainty. However, the incorporation of this trajectory into ground systems requires significant additional considerations. First, airborne systems have knowledge of present mode selection; however, it is expected that operators exchanging such a trajectory would regularly operate in anticipated modes. Second, wind forecast information between ground and air is not consistent at present due to different data sources, update cycles and blending of winds. Third, an exchanged trajectory is subject to errors of representation depending on the number of waypoints transmitted. Fourth, anticipated instructions may be known to the controller but not yet transmitted to the flight deck as a clearance and therefore not reflected. Finally, latency in transmission may lead to information being stale. For all these reasons, we assume that a ground system may use an airborne-derived trajectory to improve a prediction, but would not simply copy a provided profile.

When a clearance is provided to the flight deck, prior to the clearance being executed, a predicted trajectory is subject to additional prediction errors due to the following:

- Open clearances do not have a point at which a return instruction is known to automation. That point might be adjusted by the controller, but was not modeled.
- Voice clearances are subject to latency due to pilot response times.
- A closed clearance can be maintained by automation and delivered via voice if the controller is reminded when to issue the closing instruction. This is subject to additional errors due to latency in issuing the instruction.
- Variations in aircraft bank angle during a turn result in significant errors when the bank angle is not known to automation but assumes a nominal value instead.

Three post-clearance cases were investigated by considering the impact of the above errors on a vector clearance for resolution. A distribution of vectors' magnitudes, duration, pilot and controller latency and bank angles were applied as in [15]. The three cases investigated were:

1) Open - voice: Turn-back location was unknown to automation, latency is added to the first turn due to pilot execution and controller provision.

2) Closed - voice: Turn-back location is predicted by automation and provided to the controller, latency is added due to pilot execution and controller provision.

3) Closed – data communication: A closed clearance is provided to the flight deck including both turns. Aircraft bank angle for the turn is not exchanged. Note that the use of CPDLC does not necessarily imply a closed clearance [15].

Results in additional cross-track and along-track error are illustrated in Fig. 9 and 10 respectively. These errors are in addition to other prediction errors. An investigation of these errors by flight phase and with a variation of baseline uncertainty indicated that these post-clearance errors could be approximated as an independent error.

Each subsequent case provides a comparable reduction in peak rms cross-track and along-track error. In all cases, a residual along-track error remains as error factors affect the prediction of the duration of the vector maneuver. The lack of exchange of bank angle results in significant errors in the closed maneuver, CPDLC case. The exchange of bank angle is expected to reduce this error significantly.

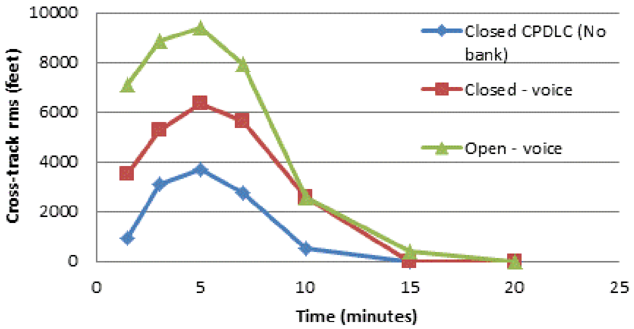

Figure 9 Additional cross-track error as a function of look-ahead time for vector maneuvers

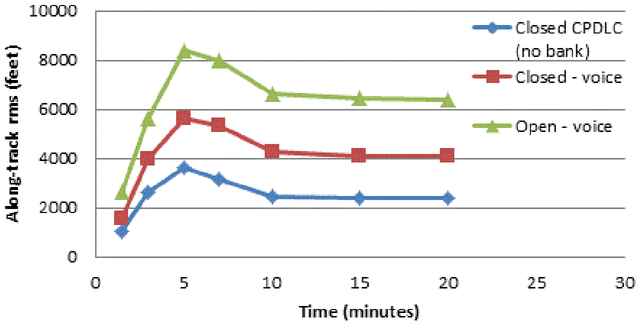

Figure 10 Additional along-track error as a function of look-ahead time for vector maneuvers

B. *Conflict Detection and Resolution*

Using the trajectory prediction error characteristics identified previously, SOC curves were obtained for conflict detection across five different areas of the NAS for the base case reflecting present-day flight information exchange. Areas were selected with different traffic properties such as traffic density, airspace structure, and percentage of climb, cruising and descending traffic (See Table I). The objective was to determine the extent of SOC variation across airspace.

Fig. 11 describes the conflict detection SOC curves at 10 minutes for level flights. Missed alerts were normalized with the number of alerts at zero buffer and false alerts with the actual number of conflicts. Airspace area 3 had insufficient level-flight conflicts to be included in this figure. Despite traffic differences, the curves are consistent.

TABLE I. PROPERTIES OF AIRSPACE AREAS

Airspace Area	Relative Density	% Climb	% Cruise	% Descent
1	100%	21%	58%	21%
2	60%	35%	61%	3%
3	211%	35%	19%	45%
4	124%	5%	78%	17%
5	149%	34%	56%	10%

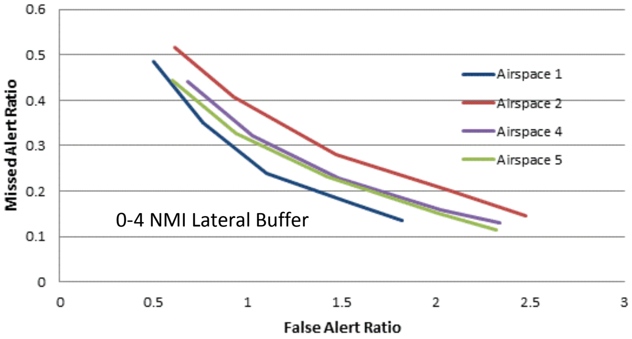

Figure 11 SOC for level flight conflicts across different airspaces

Fig. 12 shows the base case CD SOC curve at 10 minutes for alerts with one flight transitioning. Each airspace has two curves, with each curve representing the effect of the lateral buffer under the assumption of a fixed vertical buffer. As the lateral buffer is increased, missed alerts can only be reduced so quickly as many remaining missed alerts are the result of vertical errors. The expansion of the vertical buffer (by 800 feet in the figure) allows a reduction in missed alerts with a corresponding increase in the false alert rate. The effect of airspace is greater for transitioning flights than for level flights.

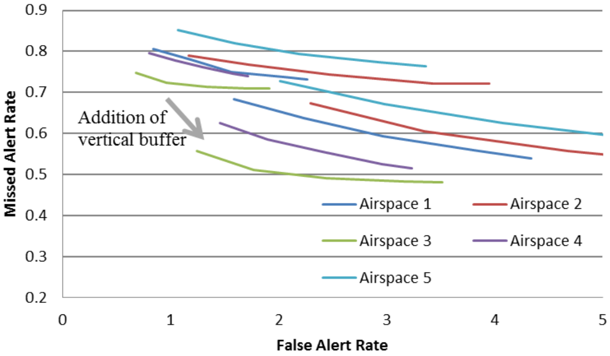

Figure 12 SOC for transitioning flight across different airspaces

Missed alert rates shown above exceed those reported previously because: the look-ahead horizon was assumed to be 10 minutes, longer than prior reports of missed alerts [22] and aircraft speed is not assumed to be adapted from surveillance updates. The effect of these two considerations reduces the uncertainty, and improves the SOC curves. Subsequent SOC curves incorporate the effect of airspeed adaptation.

Conflict detection SOC curves were computed for various cases as described in Table II. Pre-clearance cases (I-III) allow estimation of the number of displaced flights by determining the false alert rate leading to an acceptable missed alert rate. Post-clearance cases are used to estimate the buffers used for lateral resolution at a given missed alert rate. Together these help determine the additional flight displacement for CD&R and provide an indication of the additional CD&R-induced trajectory perturbation caused by prediction uncertainty.

TABLE II. CASES EVALUATED FOR CD SOC

Number	Case Description
I	Present-day uncertainty
II	Full data exchange of parameters described in Section III.A
III	Aircraft-derived trajectory improves ground prediction. Uses same accuracy as case number II
IV	Post-clearance open instruction issued via voice with present-day uncertainty
V	Post-clearance closed instruction issued via voice with data exchange
VI	Post-clearance closed instruction issued via CPDLC without bank information with present-day uncertainty
VII	Post-clearance closed instruction issued via CPDLC with bank information and data exchange

Curves describing the System Operating characteristics for these cases are shown in Fig. 13 for conflicts between level flights and in Fig. 14 for those with at least one transitioning flight. Pre-clearance cases are shown with solid lines and post-clearance cases with a dashed line. As expected, higher prediction accuracy leads to improved performance.

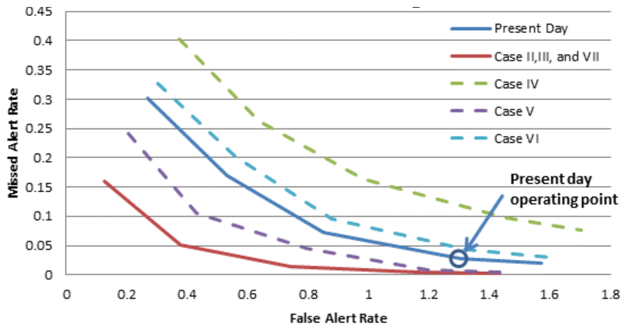

Figure 13 SOC for conflict detection under various cases for level flights (dashed lines represent post-clearance cases)

The level flight case illustrates that information exchange allows present day missed alert rates to be preserved with a lower false alert rate. As a consequence, 30% fewer aircraft would be needlessly displaced using detection as defined by Case II.

When a clearance is issued for conflict resolution, the post-clearance curves are applied to a trial planning trajectory. High missed alerts indicate that the clearance would likely have to be re-issued to deal with the missed conflict. High false alerts indicate that the resolution maneuver is more likely to have to avoid multiple flights.

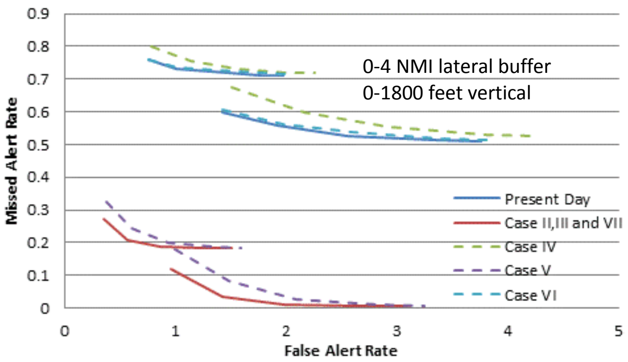

Figure 14 SOC for detection under various cases for transitioning flights

For example, if detection is conducted using a ground prediction improved through an aircraft-derived trajectory (Case III), but there is no exchange of additional parameters, a closed clearance would be generated using present-day trajectory estimation and issued via CPDLC (Case VI). In this case, the downlink helps to reduce the number of false alerts being generated. However, resolution maneuvers would be larger to offset the additional uncertainty of the post-resolution trajectory. The lack of information exchange in this case results in approximately 2 nautical miles additional lateral separation.

In the case of transitioning flights (see Fig. 14), MA rates are large with present-day levels of information exchange and trajectory prediction (Cases I, IV, and VI). This performance is predominantly driven by large vertical position errors. As a result, only the addition of large vertical buffers can provide missed alert rates below a 10% mark at this look-ahead. However, large vertical buffers increase the false alert rate as well. As a result, automated conflict detection in a transition environment with present-day ground-based prediction is infrequently used in practice.

Despite the uncertainty, aircraft are separated in transition today. Look-ahead times are shorter thereby reducing the vertical uncertainty. In low-density airspace where the conflict rate is low, large vertical buffers could be applied. As density is increased, two additional strategies can be used to cope with this vertical uncertainty:

1) *Level off:* Reduce the vertical uncertainty by assigning temporary flight levels and vertical constraints in transition.

2) *Sterilize airspace:*Ensure that there is low-density area where flights can be maneuvered to avoid conflicts with large vertical separation, essentially as a 2-D problem.

These strategies contribute to inefficiencies, either by interrupting transitioning flights, or by constraining available airspace. The imposition of procedural constraints applies inefficiencies to all flights, not just those encountering a conflict. Of the seven cases considered, only those with data exchange provided post-clearance accuracy not requiring large vertical buffers for transitioning flights at the look-ahead time investigated.

Pre-clearance curves indicate how many additional flights would be displaced, whereas post-clearance curves describe how much displacement is required. This is summarized in Table III. For transition, some cases must rely on the prior procedural separation approach unless density is low.

TABLE III. IMPACT OF EACH CASE – LEVEL FLIGHT

Case	Impact at Operating Point
I	Displace 1.3 additional flights/conflict (procedural transition)
II	Displace 0.6 additional flights / conflict (1.6 in transition)
III	Displace 0.6 additional flights / conflict (1.6 in transition)
IV	Additional 5 nmi resolution buffer (procedural transition)
V	Additional 2.3 nmi resolution buffer (+1000 vertical in transition)
VI	Additional 4 nmi resolution buffer (procedural transition)
VII	Additional 1.6 nmi resolution buffer (+1000 vertical in transition)

As flights experience conflicts, they will be subject to trajectory perturbations for resolution. The frequency of these perturbations is dependent on the base level of conflicts combined with the false alert rate at the operating point. We assume a base rate of conflicts using a Poisson process with a rate of one per hour derived using data from [20].

The distribution of magnitudes of each perturbation will depend on the distribution of conflict geometry, time of resolution and separation used for resolution. The distribution of perturbations was estimated through simulation of encounters distributed in accordance with [20] assuming an eight minute look-ahead for resolution. Fig. 15 illustrates the distribution of additional time per encounter using vectors as a function of the cases used for detection and resolution. Altitude maneuvers during cruise induced significantly smaller time perturbations, but similar magnitude variations for level-off segments.

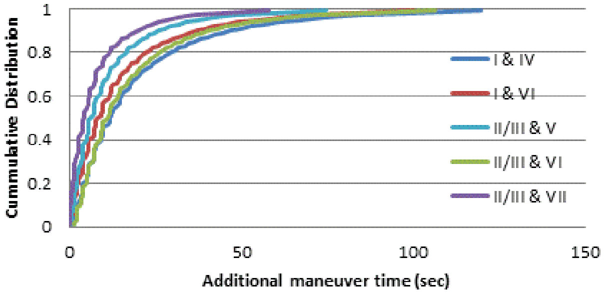

Figure 15 Additional maneuver time distribution dependent upon detection and resolution case (vectors)

The combined effect of the detection and resolution on trajectory perturbation was computed and is illustrated in Fig. 16. Cases in transition are shown with a “T” in parentheses. Averages and standard deviations for each case are shown in Table IV. The most direct consequence of these delays is additional fuel and time costs. These numbers also represent a 20 to 40% additional variation over the base cases, together with a corresponding shift in the mean as well. As a result, applications with longer time horizons than CD&R have to face correspondingly greater levels of prediction uncertainty stemming from these additional perturbations.

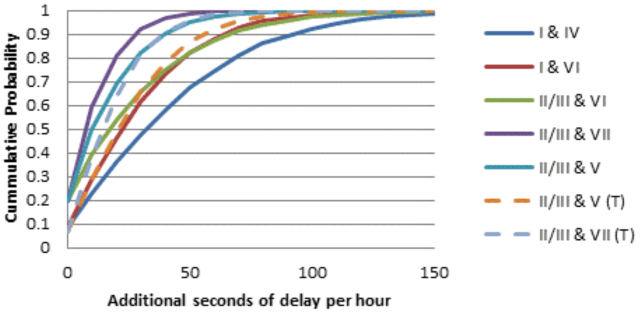

Figure 16 Additional delays due to vectors for conficts (per hour)

TABLE IV. ADDITIONAL CONFLICT MANEUVER DELAY PER HOUR

Case	Mean Delay (sec)	Standard Deviation (sec)
I & IV	41	38
I & VI	28	26
II/III & V	16	18
II/III & VI	26	29
II/III & VII	11	12
II/III & V (T)	26	22
II/III & VII (T)	18	15

C. *Flow Impact*

The effect of trajectory prediction uncertainty on flow management is described here through an example. A collection of 883 flights are subject to a capacity constraint at an arrival airport. Flights are assigned a controlled time of arrival (CTA) to ensure demand does not exceed capacity at the arrival airport. This assignment occurs at specific planning times with slots rationed in accordance with the initial planned arrival time. Airborne flights are prioritized (their slots are assigned first) and then flights still on the ground at a given planning time are assigned an arrival slot with a corresponding controlled departure time (CDT). Once a flight is airborne, trajectory prediction errors result in a shift in the estimated time of arrival (ETA) relative to the CTA. The flight is controlled through speed or vectors to meet the CTA. Control through speed is preferred, but limited by aircraft speed margins (estimated using min/max RTA data from operational flight trials). As a result, fuel-consuming vectors are required when speed alone cannot absorb delay. When uncertainty results in an ETA being too late to meet a CTA through speed control, the arrival slot will be missed by the late flight. In this case, dynamic re-scheduling may enable some flights with margin remaining to take advantage of the slot.

The flow management example was run using four control strategies as describe in Table V. One example case (Case 0) does not impose any flow management. In all other cases with flow management, the arrival schedule is dynamically adjusted as some flights are expected to miss their CTAs. The differences between the flow strategies have to do with when control begins. Flights described as exempt do not have a controlled departure time assigned to them; however, upon reaching a specified distance to the arrival airport, their time of arrival is controlled.

The objective of this example was not to compare the performance of flow management strategies, but to indicate the performance impact of trajectory prediction uncertainty as described previously. To this end, four performance metrics were evaluated via Monte Carlo simulations: additional fuel required (Fig. 17), ground delay per flight issued a CDT (Fig. 18), airborne strategic delay (Fig. 19), and tactical delay discussed below. Tactical delay refers to the delay required upon arrival to meet arrival capacity constraints via an inter-arrival time. Additional fuel did not include that required for tactical delay. Departure uncertainty was not included as this study sought to isolate airborne uncertainty.

TABLE V. TFM STRATEGY CASES EVALUATED

Strategy	**Description**
0	Baseline case with no flow management. Flights depart on schedule and delays are assigned tactically on arrival.
1	Close-in flow management. Flights are metered to arrival slots at about an hour in. Flights within 500 nautical miles are delayed on the ground, and scheduled after airborne flights.
2	Extended case of 1. Flights are controlled beginning at 3 hours, and flights are exempt beyond 1500 nautical miles.
3	Limiting case of 1. No flights are exempt. All flights are controlled to meet the schedule.

Under the most tactical scenario (Strategy 0), an average of 2.8 to 3.2 minutes per flight of delay are taken tactically with the higher number reflecting high uncertainty. Strategy 0 did not contribute to the measures in Figs. 17-19. This tactical delay reduces to a range from practically zero to 40 seconds per flight across all cases with flow management. In all cases higher uncertainty results in more tactical delay. The more strategic cases result in an initial fuel savings as a result of delay being apportioned through speed reduction versus vectors. As uncertainty is increased, more control is required to meet the schedule resulting in more vectors and speed increases as speed margins are exceeded. More strategic control also reduces the ground delay required per flight as total delay is assigned to more flights on the ground. However, more strategic scenarios result in airborne and total delay that is more sensitive to uncertainty.

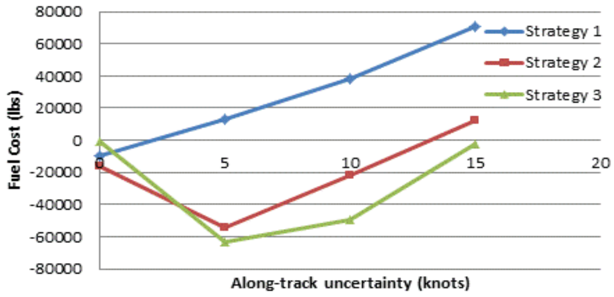

Figure 17 Additional Fuel versus uncertainty

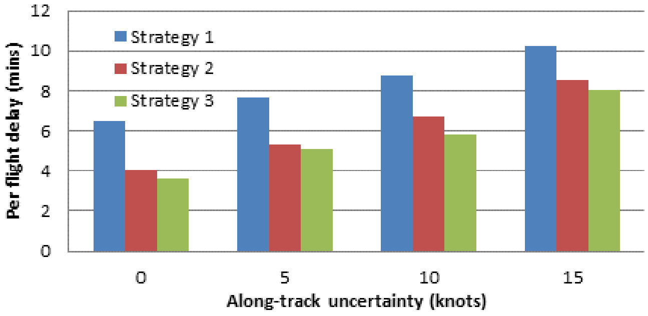

Figure 18 Ground delay per affected flight versus uncertainty across strategies

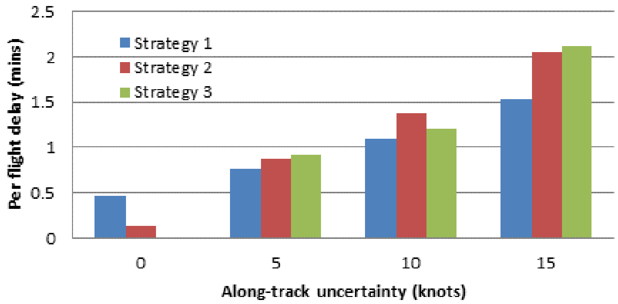

Figure 19 Average airborne delay per flight

The impact of conflict detection will depend on the strategy that is applied. Greater levels of uncertainty lead to additional cost penalties through a combination of fuel and delay. The combined level of uncertainty described previously ranged from 8.3 knots to 17 knots with speed adaptation. In practice, speed adaptation would not be as effective for longer look-ahead times. Regardless of TFM strategy used, improved trajectory accuracy reduces its impact on: fuel by 60 pounds per flight, ground delay by 2.23 minutes per flight within the program distance, and airborne delay by 50 seconds. These numbers apply to this example scenario which was not highly constrained on arrival capacity (demand exceeded capacity for only 3 hours of the day).

V. CONCLUSION

The impact of improved trajectory prediction through improved information exchange and through delivery of closed clearances was investigated. The impact on prediction accuracy was obtained using a simulation validated against operational data. The effect of information exchange and method for clearance delivery was investigated on pre- and post-clearance trajectory accuracy. Post-clearance accuracy could be improved by a factor of three over present operations for lateral maneuvers. Improved data exchange yielded similar improvements in along-track and factor of 3-4 improvements in vertical accuracy.

The subsequent impact on conflict detection and resolution indicated that CD&R SOC were consistent across differing airspace. Fewer false alerts can reduce the number of aircraft displaced, and improved post-clearance trajectories can reduce the required displacement per flight. This can reduce the additional conflict perturbation by up to 3.5 nautical miles per hour per flight.

The impact of the trajectory prediction uncertainty on TFM was illustrated through an example indicating that improved prediction accuracy can yield reduced delays and improved fuel consumption.

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NOTICE

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