

Characterization Method for Determination of Trajectory Prediction Requirements

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Concepts for trajectory-based operations depend heavily on the performance of the underlying trajectory prediction capability. To address the system-level question “how good of a prediction is good enough?” a fast-time simulation method is presented. Modeling and simulation lends itself to capturing the sensitivity of a concept’s critical performance criteria, to the performance of its supporting trajectory-prediction capability. Given the significant initial cost to develop and validate an appropriate simulation tool a characterization method is proposed to provide quicker, yet less precise results in the interim. The analysis characterizes the trajectory-prediction errors associated with key modeling options for a specific concept. Concept developers can then identify the relative sizes of trajectory prediction errors associated with key modeling options, and qualitatively determine which options would lead to the failure of their concept. The characterization method is demonstrated for a case study involving future airport surface traffic management automation. Of the four sources of error considered in this study, the average variation from the baseline trajectory associated with acceleration segments is 10%; the average variation associated with turn modeling is 4%; and the average variation associated with taxi-speed estimation is 29%. These results and the judgment of the concept developer indicate that potential error associated with accelerations segments is unacceptable, the potential error associated with turn modeling is acceptable, and the potential error associated with taxi-speed estimation is of concern and needs a higher fidelity concept simulation to obtain a more precise result. These results point to some specific surface-automation trajectory-prediction requirements that can be implemented right away while modeling and simulation tools are developed to determine other requirements in greater detail.

I. Introduction

One objective of the Next-Generation Air Transportation System (NextGen) transformation is to transition to trajectory-based operations (TBO) for managing the National Airspace System (NAS).¹ TBO uses four-dimensional (4-D) trajectories to manage traffic. High-density TBO will likely require significantly greater trajectory prediction (TP) accuracy than that achieved by the current state of the practice. TBO will also likely require a seamless interface among disparate trajectory predictors (TPs) serving multiple types of airborne and ground-based automation systems.² A key step to improving trajectory prediction is to understand the current capabilities of and future requirements for trajectory predictors. Answering the question of how to determine future TP requirements for NextGen is difficult but essential. In particular, it is important to match the requirements of the TP to the needs of the automation system it supports. If a specific TP is unable to meet the performance requirements of its client automation system, then the success of the system depends on at least one of two actions: either the TP and supporting infrastructure (e.g., source of track, intent, and wind-forecast data, etc.) must be improved, or the operational concept for the automation system must be adapted to work with the TP performance provided.³ It is desirable not only to establish the minimum TP requirements for the “client” automation application, but also to build a TP that meets those requirements while minimizing complexity and avoiding unnecessary cost and complexity. Prior work investigating the current state of TP requirements and capabilities include a workshop with MITRE’s Center for Advanced Aviation System Development and NASA, a survey of TP requirements

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conducted by a team of TP experts from (but not limited to) the Eurocontrol research labs, the Federal Aviation Administration (FAA), and NASA, and a recent survey of trajectory prediction requirements for future applications being developed at NASA.

Senior technical leads from MITRE Corporation's Center for Advanced Aviation System Development (CAASD) and NASA met for a two-day workshop (December 1999) to capture TP requirements for a small set of disparate air traffic management (ATM) automation applications.⁴ The results of the workshop, captured in an annotated briefing to NASA, CAASD and the FAA, included a side-by-side comparison to highlight the similarities and differences of the major TP requirements and capabilities for each application. This exercise provided an initial understanding of both the high-level similarities and differences in the TP capabilities supporting these applications, as well as insights about how to compare TP requirements and capabilities. However, a major impediment was the lack of documentation of the discriminating details for each TP. Five years later, the United States-Europe ATM R&D Action Plan 16 (AP16) for Common Trajectory Prediction Capabilities conducted a broad survey requesting details on the trajectory predictor requirements and capabilities (in any form) from approximately 20 research and operational organizations on several continents. The request described the specific aspects of trajectory prediction for which information is needed. Key technical leads were contacted directly through a formal letter of request, email, and follow-up phone calls. Many organizations indicated they had nothing to offer. Of the few that did respond with relevant details, the content varied widely from one organization to another, the material was inconsistent in what was documented, i.e., little comparable overlap from one organization to another and the scope of information provided was significantly incomplete. A recent survey was conducted at NASA where the technical leads of 5 of NASA's 10 ATM research focus areas were interviewed.⁵ Unfortunately, even with the lessons learned from the prior research, the survey uncovered few trajectory predictor requirements. Of those obtained most were incomplete TP requirements for existing research systems or a description of the TP capabilities from a legacy system. Few requirements were defined for the performance or functionality of the predictor. The requirements described were often confused with the higher level automation system requirements, e.g., what a conflict probe was supposed to do as opposed to what TP performance a conflict probe needed to succeed. Some researchers were not sure how they would determine the requirements needed for their future concepts and requested help. The findings of these previous efforts led directly to the objective of this paper, namely the development of a method for determining TP requirements to enable researchers to define the TP requirements for future trajectory-based automation concepts and systems.

The paper begins with a background summary of a recent NASA survey of TP requirements. The paper then investigates alternative options for determining quantitative TP-performance requirements. A method of TP error characterization is then introduced to show a direct relationship between some key TP functional and non-functional (performance) requirements. The purpose of this method is to identify the characteristics that must be modeled, at a minimum, to achieve a desired TP performance level. An initial application of this analysis to surface operations is provided as an example that can be further expanded upon for surface concepts or generalized to other applications. The results will contribute toward defining prediction capabilities required for the future air transportation system as well as work plans for future trajectory predictor development. This process is expected to facilitate establishment of the definitions of quantifiable requirements and performance metrics to be established.

II. Background - NASA TP Requirement Survey

The survey was conducted through a series of interviews with leading researchers at NASA. The technical leads of 5 of NASA's 10 ATM research focus areas were interviewed. Each interview represented a separate research area at NASA applicable to the NextGen vision: (1) surface operations, (2) super-density operations, (3) separation assurance, (4) traffic flow management, and (5) dynamic airspace. Each interview began with questions about the "client" application(s) that require trajectory predictor capabilities, typically decision-support automation or a simulation. Next, the interview questions explored the needs of the client applications. In some cases, existing TP capabilities were already in use and adequate to support some of the research. In other cases, new capabilities were required to support the client applications for future concepts.

The questions regarding client needs were organized into four areas based on the four main TP-related processes: preparation, trajectory prediction, trajectory prediction update, and the export process.⁶ The preparation process began with the basic input to the TP including current, estimated aircraft state and flight plan. Based on the input, the output of the preparation process included the input to the TP and all of the instructions required to control the integration within the trajectory prediction process. These instructions detailed the pilot intent to be modeled and how the transition between sequential flight segments is to be performed. The preparation questions asked about inputs to the TP and the integration instructions. An example of an interview question regarding the preparation

process was “how will the movement and position of the aircraft be modeled?” The trajectory prediction process calculated the trajectory using the information from the preparation process and the supporting models of the forecasted wind, temperature and aircraft performance. The prediction part of the interview investigated the methods used to compute the trajectories, for example what form of the equations of motion was used. The interview then addresses the trajectory prediction update process. These questions involved the conditions and/or frequency for which updated predications are needed, and the specific purpose for the update. Finally, the export process addresses the expected content and format of the TP output. The interview concluded with questions regarding the desired accuracy of the predicted trajectories.

While the objective of the survey was to document trajectory predictor requirements for future automation systems, but few requirements actually resulted from the survey. For all of the research areas interviewed, requirements on future trajectory prediction have not been adequately considered. The actual responses provided information at more of a higher automation system level, instead of at the level of the trajectory predictor within the system. As a result, the collected interview responses fit into three categories: an incomplete requirement for a future trajectory predictor, an existing requirement or capability for a legacy automation system, or an ambiguous response that doesn’t clearly fit into either of the previous categories, but which may be a requirement for the trajectory predictor or the automation system. Very few requirements were defined for the functionality or performance of the predictor in any of the research areas. Table 1 is the response to the question “Have any performance requirements been defined for the future trajectory predictor?” In all areas interviewed the answer is “No.” In all cases the researchers do not know what performance is required for their future system. The responses given did not provide enough information to form a requirement for the trajectory predictor. For example, for surface operations the trajectory must be very accurate for monitoring conformance and conflict detection and resolution, but this accuracy cannot be quantified. In many cases, the researchers are not sure how to determine TP requirements and request help with this task.

Table 1: Have any performance requirements been defined?

Surface Operations	No. Trajectory must be very accurate for monitoring and conflict detection and resolution.
Super-Density Operations [Terminal]	No. Requirements are being investigated but none are currently defined.
Separation Assurance [En route]	No. Trajectories need to be as accurate as possible with uncertainty below separation standards (5 nmi, 1000 ft).
Traffic Flow Management	No. Trajectory error is too high; any error reduction will be an improvement.
Dynamic Airspace	No. Requirements will be a function of the airspace complexity or performance boundaries of the TP.

III. Process for Determining Requirements

The NASA survey confirms the need to establish a process to help developers determine their trajectory predictor requirements, especially performance requirements for their future concepts and research-prototype ATM automation systems. The performance requirements for a system, if defined, drive a great portion of the functional requirements. The research community tends to use functional requirements to represent algorithmic and software design choices. In this context, the functional requirements are actually intended to serve as surrogates for implicit performance requirements. However, if functional decisions precede the definition of performance needs, the performance of the system may be unnecessarily limited if not insufficient. For example, if TP accuracy in the

horizontal plane would accommodate errors of up to 5-10 nmi, depending on the operational envelope for each aircraft type, atmosphere and turn model, the simplest model of an instantaneous turn may provide the needed accuracy with minimum complexity. On the other hand, if the performance requirements call for ground track prediction accuracy of errors equal to 1 nmi or less, a more sophisticated turn model would be indicated. Ultimately, the goal is to achieve the required TP performance with minimum cost and complexity while accounting for the life-cycle costs associated with daily operations such as system maintenance, upgrades and decommissioning. Once the client automation system or concept has defined the performance requirements for its supporting TP, the definition of functional requirements is a more rigorous and straight-forward task.

The results of the NASA survey also imply that researchers are attempting to design TPs without having well-defined trajectory prediction requirements. The risks involved with this approach are significant. One major consequence is a TP that does not meet the needs of the client automation system or operational concept. In this case, the developer can attempt to change the TP in the hope that the changes will help the client automation meet the performance requirements of the application. Examples of performance requirements for the client automation may range from subjective measures, e.g., controller acceptance, to objective measures such as the rate of conflict prediction false alarms and missed alerts. Alternatively, the developer may change the corresponding operational concept to adapt to the performance limitations of their supporting TP. In this case, the operating envelope for the concept may need to be restricted, or the goals and benefits of the automation system must be reduced, if not changed, to adapt to the most productive use of the capabilities of a particular TP. Changing the operational concept may be met with some resistance from the stakeholders who “own” the original need that will remain unfulfilled. For example, it would be problematic for an airline launch customer to accept delivery of a new aircraft type that failed to meet the requirements necessary for the airline to open up new routes. Such an airline launch customer would be unlikely to accept delivery of the underperforming aircraft (i.e., adapt their mission to the capabilities of the aircraft type) but instead cancel delivery in favor of finding an aircraft type that better suits the business needs of the airline.

Consequently, it is generally crucial to determine system requirements early enough to ensure both a feasible concept and the ability to develop and deploy the systems necessary to achieve the concept’s goals. Altering the TP will involve additional effort and costs along with the addition of significant risk to the schedule for research, system development, or deployment. Even with the additional effort it may not be possible to meet the desired system-level performance with the existing system architecture of the TP. The objective of the work presented in this paper is to establish a process to determine trajectory predictor requirements, particularly performance requirements, for future automation systems.

The method of finding TP requirements proposed in this paper has two parts: 1) objectively quantify the performance requirements for the automation system or TP client, and 2) determine the sensitivity of the automation system’s performance to the performance of the underlying TP. Before requirements for the TP performance can be defined, the automation concept itself must have a clear and complete set of performance requirements at the application or client-automation-system level. The critical TP performance requirements are directly dependent on the unique performance requirements of the automation system itself. The choice of performance metrics is the responsibility of the TP client stakeholder. This information must be defined for the client application before seeking to define the TP performance needed by the client application.[§]

Another prerequisite to determining performance requirements is to understand the relationship between the performance of an automation system and its supporting trajectory predictor. There are two parts of this relationship of interest: the sensitivity of the automation system performance to the TP performance, and the sensitivity of the TP performance to key functional components of the predictor (including inputs to the predictor and models and algorithms used for prediction). It is in determining this sensitivity where this research can aid TP clients.

There are numerous possible approaches to determine the sensitivity discussed previously. This work considers an analytical approach, a real-world experiment, a human-in-the-loop (HITL) simulation, and a fast-time simulation. An analytical approach, while having the potential to provide the fastest results, faces significant challenges. TP performance is multi-dimensional, time-varying, and non-linear—not the best form for an analytical approach to model the TP performance, let alone the sensitivity of the client automation performance to the TP performance. It will be very difficult, if not nearly impossible, to derive an analytical expression representing a wide range of conditions and error possibilities for the trajectory-predictor performance. A real-world experiment to study the sensitivity will require personnel and equipment over an extended period of time. The costs associated with this type

[§] Acceptable TP performance is necessary but not sufficient for the success of the client automation and concept. Other factors include the performance of the automation-system algorithms, user and system interfaces, procedures, and human factors.

of experiment will be very high, data collection will be limited, and only a limited number of cases can be studied. A HITL simulation will introduce greater experimental control, but there will still be significant costs associated with personnel; that will limit the number of cases significantly. While a fast-time simulation approach will be missing the human element, it can be much more cost and time-efficient than the real-world experiment or HITL simulation. Setting the sensitivity analysis aside, however, the HITL simulation approach will provide an excellent way to address step one above: to help the clients of TP (automation system/concept developers) determine the performance requirements for their automation system.

For the purposes of this work, a fast-time simulation approach is the preferred method to determine the sensitivity. With this approach, a modeling and simulation platform will be used to evaluate the effects of several factors on TP performance and their impact on the automation system performance. With such a platform, the performance of an automation system/concept can be modeled and evaluated as a function of TP modeling assumptions under a wide range of operational conditions, aircraft performance errors, and input uncertainty. This approach will serve as the basis for establishing relationships between TP performance and automation system performance. However, even with the advances in ATM modeling and simulation such as the Airspace Concept Evaluation System (ACES),⁷ the development and application of this approach to a specific automation system/concept may take a year if not longer before results can be produced. An alternate method is needed to start progress towards determining TP performance requirements now while the fast-time simulation approach is being further developed. The characterization method presented in the following paragraphs provides a way forward.

IV. Characterization of TP Errors

The characterization method described in this paper can help trajectory predictor clients begin to approximate performance requirements by providing a relatively quick and easy way to study the sensitivity of TP performance to critical TP modeling decisions. The objective of the characterization is to identify potentially critical modeling characteristics that affect the TP's ability to meet the requirements for the client automation system performance. Identifying the critical modeling characteristics allows the TP client to begin developing minimum performance requirements for these characteristics. The characterization method begins with choosing modeling characteristics that are likely to be vital to the performance of the TP. Modeling characteristics refer to the dynamics, variables, and parameter values that may be involved in computing trajectories. The critical modeling characteristics will vary depending on the domain in which the TP is applied and its dependent automation applications. The next step is to define metrics and test conditions that will excite problems or behaviors of interest in these modeling characteristics. With these metrics and test conditions defined, the next step is to compute the trajectories. Finally, present the results—the sensitivity of the trajectories to the modeling decisions—to the client. The client evaluates these results to judge the impact of potential errors on the automation system caused by the modeling decisions made. This is a first step in performance requirements development. In this paper, the characterization method is applied to the surface operations research area as an example. At the time of this work, the surface operations research area did not have a four-dimensional trajectory predictor to be used in the NextGen, but was beginning development. For this reason, the surface operations research area is a suitable choice for the application of characterization method.

The surface operations research area is focused on enabling high-density operations on the surface and immediate airspace around an airport.⁶ The approach is to develop and evaluate new concepts and algorithms for a wide variety of surface automation applications. These applications include taxi planning and surface-traffic optimization, taxi-clearance conformance monitoring, conflict detection and resolution, collision avoidance, and the mitigation of environmental impacts. Ground-based and flight-deck solutions will be based on the prediction and monitoring of 4D trajectories for both departure and arrival traffic on and near the surface. The 4D trajectories will describe how the aircraft (and other vehicles) will move along the surface including major intersection points and the arrival times for each point.

The requirements for the TP to support these applications have not yet been defined. The researcher is able to provide some general and partial requirements for the TP, but this list is far from complete. The general requirements are primarily in the form of prediction time horizon. The time horizon requirement for taxi planning is 30 minutes, 5 minutes for conformance monitoring and 20 to 30 seconds for collision avoidance. While there are no TP accuracy performance requirements per se, the researcher felt that a kinetic (force-based) performance model will be required. The TP will also require actual and forecasted weather information as an input, such as rainfall and icing, along with a model of how weather conditions will affect surface traffic movement.

A challenge for surface operations is computing the estimated time of arrival (ETA) of the aircraft at different places of interest along its taxi route. Trajectories are used to compute ETAs for managing aircraft crossing a runway, managing the usage of intersections, and determining the location of an aircraft along its taxi route at any

given time. Better ETA predictions are needed for the cases mentioned above for scheduling, conflict avoidance, detection, and resolution purposes.

The objective of the characterization method applied to surface operations is to evaluate the effects of the modeling decisions made for trajectory prediction on the total surface trajectory durations. The modeling decisions include determining what modeling characteristics will improve trajectory predictions for the surface automation applications. Four types of modeling characteristics are considered in this example of the characterization method. These four modeling characteristics represent potentially critical dynamics, variables, or parameter values to model that affect the performance of the surface trajectory predictor. The modeling decisions related to these four modeling characteristics are illustrated in Figure 1 which is a representation of a taxi route.

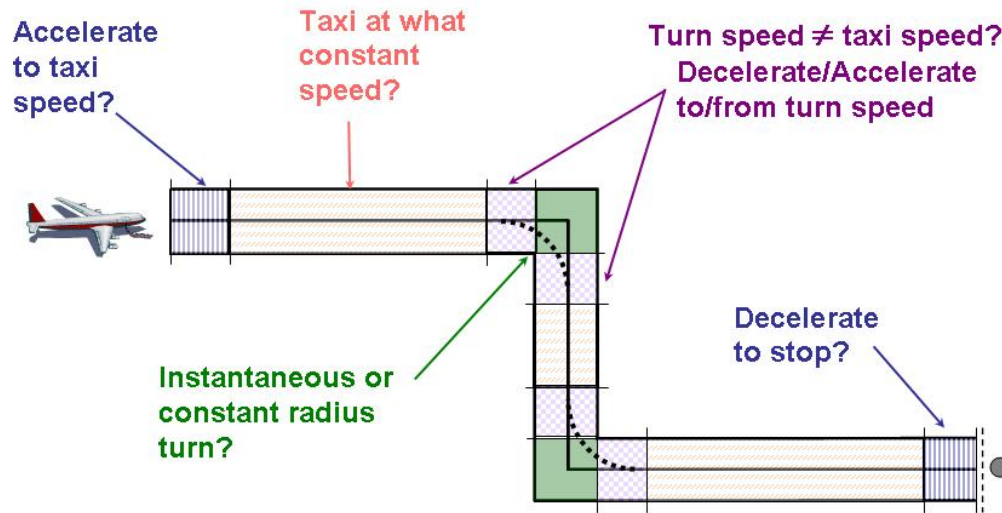


Figure 1: Surface Modeling Decisions

The different color regions represent different modeling techniques for surface trajectory prediction along the route. The first modeling characteristic to consider in the figure is acceleration. Specifically, how will the trajectory predictor model how the aircraft will accelerate to the desired taxi speed from a stop or decelerate from the taxi speed to a stop? The next modeling characteristic is the taxi speed. Will the TP model the aircraft to travel at a constant taxi speed or will the speed vary along the path? There are also a few decisions involved for aircraft approaching a turn. Will the turn speed be different from the designated taxi speed? If so, will the TP model deceleration to and acceleration from the turn speed? Furthermore, will the path of the turn be a point where an instantaneous turn occurs or a constant radius arc or some other representative path?

To determine the effect of the modeling decision made regarding each characteristic on the trajectory, the duration of a specified taxi trajectory is computed using basic equations relating distance, velocity, acceleration and time under the conditions described in Table 2. The durations calculated are for unimpeded taxi trajectories. To study the impact of the predicted taxi speed on the trajectory duration, trajectories are computed with off-nominal values of taxi speed from +/- 1 up to +/- 5 knots from the nominal value. A constant taxi speed with a nominal value of 15 knots is used. In the surface operations example, instantaneous acceleration and constant acceleration are two methods considered for handling acceleration when computing trajectories. Points of acceleration of interest are acceleration of the aircraft to the desired taxi speed from a stop and deceleration from the desired speed to a stop. The duration of the trajectory is computed using both methods in this analysis. However, stops are only considered at the endpoints of the route, not along the route. The value of constant acceleration used is 2 ft/s^2 . The trajectory time is also computed for trajectories modeled with instantaneous turns versus constant-radius turns and constant deceleration into and constant acceleration out of the turns to characterize the turn dynamics. The total trajectory times computed for each condition are compared to a chosen a computed baseline time to determine the prediction time differences resulting from the speed model, acceleration model to and from a stop, the turn path model, and the model for decelerating to turn speed when entering a turn then accelerating back to the taxi speed at the exit. The details of the conditions used to calculate the trajectory time and the description of each baseline case are shown in Table 2.

Table 2: Characterization Test Conditions

Modeling characteristic	Description of test conditions
Speed	Constant taxi speed, instantaneous turns, instantaneous acceleration
<i>Baseline</i>	<i>Taxi speed of 15 knots, instantaneous turns, instantaneous acceleration</i>
Acceleration to/from stop	Constant taxi speed, instantaneous turns, constant acceleration
<i>Baseline</i>	<i>Constant taxi speed, instantaneous turns, instantaneous acceleration</i>
Turn model	Constant taxi speed (no slowing for turns), turn modeled with curve segment length, instantaneous acceleration
<i>Baseline</i>	<i>Constant taxi speed, instantaneous turns, instantaneous acceleration</i>
Deceleration to turn speed	Constant taxi speed, turn modeled with curve segment length and constant turn speed (less than taxi speed), constant acceleration, and deceleration to turn speed
<i>Baseline</i>	<i>Constant taxi speed, instantaneous turns, instantaneous acceleration</i>

Three example taxi routes are selected to test the four modeling characteristics. The three routes are chosen from the map including most of the Dallas–Fort Worth International Airport. The routes represent typical taxi segments from the terminal to a runway or vice versa. The varying routes are chosen to excite behaviors of interest in the modeling characteristics. As can be seen in Figure 2 and Table 2, each route varies in total distance and number of turns to be traversed. Table 2 shows the nominal taxi time for each route. The nominal taxi time is the computed total trajectory duration for a baseline reference.

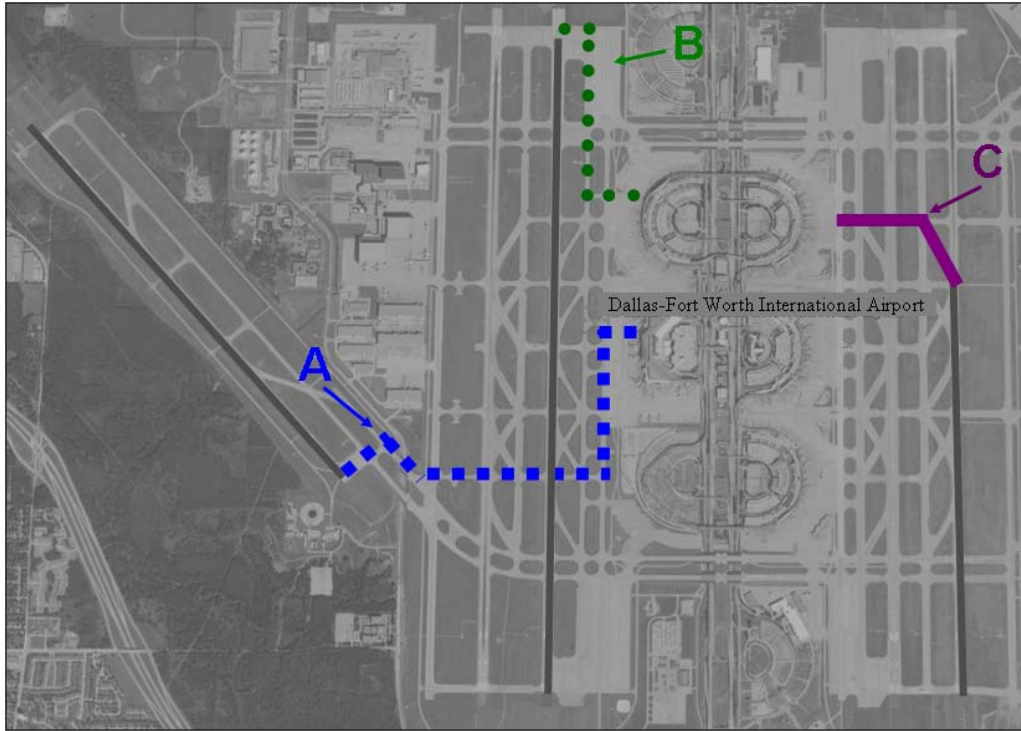


Figure 2: Taxi Route Descriptions

Table 3: Taxi Route Descriptions

Taxi Route	Taxi Distance (nmi)	Taxi Time (sec)	Taxi Speed (kts)	Number of Turns	Sum of Turns (deg)
A	1.35	325	15	5	400
B	0.81	194	15	3	180
C	0.46	110	15	2	80

V. Characterization Results

The trajectory duration is computed for each modeling characteristic and the corresponding baseline case. Figure 3 shows the trajectory time differences in seconds. The figure illustrates the effect of the modeling decisions on the total surface trajectory duration.

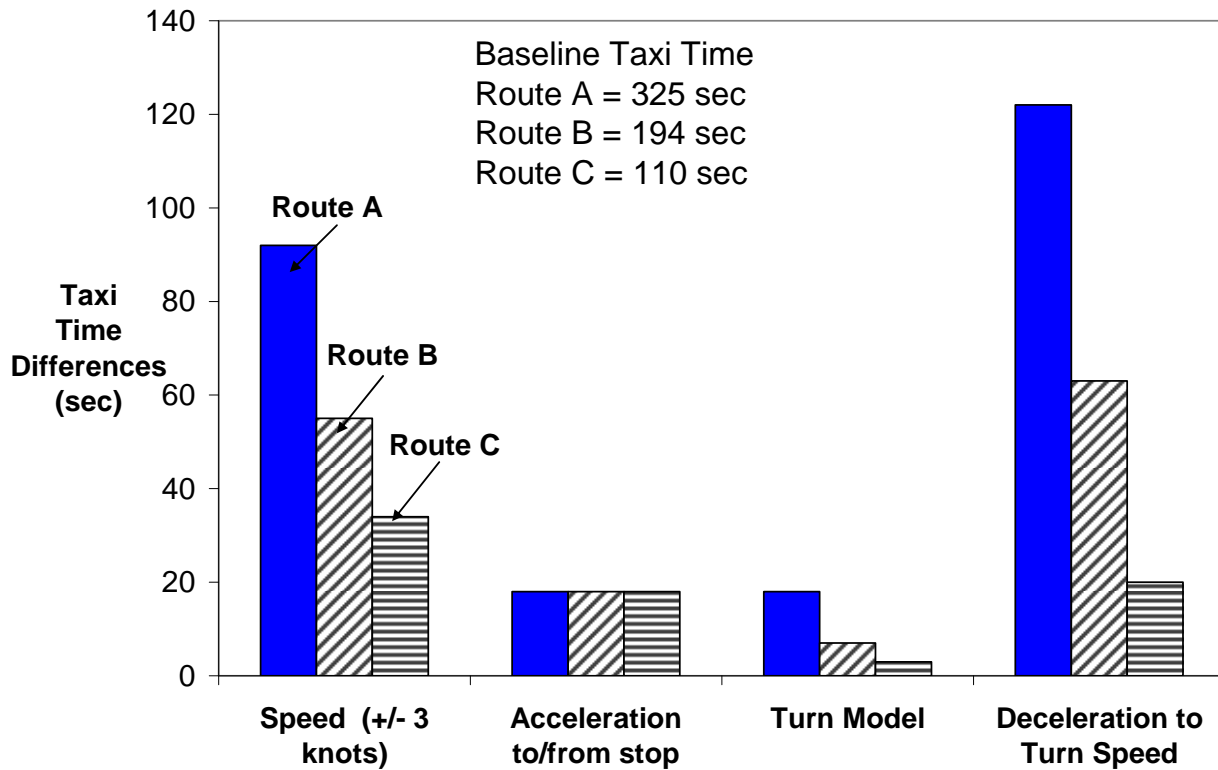


Figure 3: Trajectory Time Differences

For route A, there is a 92-second difference resulting from three knots of deviation from the predicted (nominal) taxi speed. This variation accounts for 28% of the total trajectory duration. The resultant prediction time difference from modeling versus not modeling the deceleration to a slower turn speed for route A is 122 seconds, which is 38% of the total trajectory time. The time variations caused by not modeling accelerations to and from stop and the decision to model an instantaneous versus a constant-radius turn each are 6% of the total trajectory duration. Similar results can be seen for routes B and C. The average differences resulting from each modeling decision for the three routes can be seen in Table 4.

Table 4: Average Trajectory Duration Difference

	Speed Error (+/- 3 knots)	Acceleration to/from stop	Turn Model	Deceleration to Turn Speed
Percent of Average Difference	29	10	4	29

With the trajectory analysis complete, the final and most important step of the characterization method is to present the results to the automation system client or subject matter expert. From the figure, the client can see the magnitude of potential variations caused by the TP modeling choices. Presenting these results to the client of surface operations reveals that, for the applications of the surface TP in this work, the difference associated with accelerations segments is unacceptable, the difference associated with turn modeling is acceptable, and the difference associated with taxi-speed estimation is of concern and needs a higher fidelity concept simulation to obtain a more precise result. This judgment is dependent on the operational domain and applications dependent on the trajectory predictor. In this case, the client can conclude that, at the minimum, the trajectory predictor for surface

operations must have accurate models of the taxi speeds, turning speeds, and the transition between them for each aircraft to avoid critical prediction errors.

VI. Conclusion

The objective of this research is to define a process for determining future trajectory predictor requirements. While a modeling and simulation approach may provide a way to determine the trajectory predictor performance needed to support future concepts, the approach will need to be developed and validated for at least a couple of representative cases. In the meantime, the characterization method introduced in this paper provides a relatively quick and simple way to begin defining trajectory predictor performance requirements. Airport surface operations are analyzed to demonstrate this method for providing a relatively fast, order-of-magnitude understanding of the impact of modeling factors on the predictor performance. Results indicate and the client confirms that the difference associated with accelerations to and from turn speeds, averaging 40% of the total trajectory duration, is unacceptable and the difference associated with taxi speed, averaging 29% of the total trajectory duration, is of concern and requires further study. The characterization allowed the client to approximate the trajectory predictor accuracy needs based on consideration of the magnitude of typical errors that may occur due to modeling dynamics and expert judgment on the impact of those errors on client performance.

The next steps for this research include enhancing the characterization of the surface applications by a comprehensive analysis of recorded surface trajectory data and identifying and characterizing other important modeling characteristics for surface-trajectory prediction. The characterization will also be applied to other clients. A more important, long-term step is to develop and use the fast-time modeling and simulation approach to study the sensitivity of the performance of an automation concept or application to the performance of its underlying trajectory predictor.

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