Trajectory Design for Aircraft Taxi Automation to Benefit Trajectory-Based Operations

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Abstract—Trajectory-based operations constitute a key mechanism considered by the Joint Planning and Development Office (JPDO) of the U.S. for managing traffic in high-density or highly complex airspace in the Next-Generation Air Transportation System (NextGen). With this concept applied to surface operations at major airports, current research has been exploring the use of surface 4-dimensional (4D) trajectories, which require the taxing aircraft to meet required times of arrival (RTAs) at selected locations along the taxi route. Observing these RTAs as constraints along the taxi route, the flight still has many degrees of freedom in adjusting its state profiles (i.e., position, velocity, etc. as functions of time) to achieve the timing constraints. Previous research has applied the trajectory control freedom to assure passenger comfort by keeping the accelerations and decelerations within prescribed limits. This paper explores untapped flexibility in the trajectory design problem to achieve additional desirable behaviors, beginning with the consideration of fuel burn, emissions, and noise. A flight-deck automation experimental prototype serves as the platform for evaluating the designs. The findings will benefit future designs of flight-deck automation systems, as well as tower automation systems which rely on accurate understanding of the flight deck’s operational behaviors to plan efficient and safe operations for the entire surface traffic.

I. INTRODUCTION

TRAJECTORY-BASED operations constitute a key mechanism proposed by the Joint Planning and Development Office (JPDO) in the Next-Generation Air Transportation System (NextGen) Concept of Operations (ConOps) [1] for managing traffic in high-density or high-complexity airspace. Applying this mechanism to surface operations at major airports results in the use of 4-dimensional (4D) trajectories to enable safe and efficient surface operations.

The FAA’s NextGen Implementation Plan [2] recognizes airport congestion as a major problem of the National Airspace System (NAS). The plan includes airport expansion plans to build new runways, extend existing runways to accommodate larger aircraft with higher passenger capacities, relocate runways to increase lateral separation to allow parallel operations under Instrument Flight Rules (IFR), and build additional taxiways to accommodate the increased surface traffic. Successful implementation of these expansion plans means more complex airport layouts for the major airports, and more traffic operating on their surfaces. For airports with added runways, more flights need to cross active runways. Furthermore, new technologies that improve runway capacity through reduction in longitudinal separation will reduce the opportunity for active-runway crossing, compounding the runway-crossing problem. Major airports such as Dallas/Fort Worth International Airport (DFW) exemplify such complexity with as many as 7 runways. Trajectory-Based Surface Operations (TBSO) use more-precise maneuvers for navigation across runways and through taxiway intersections to reduce operational uncertainties and improve efficiency. They require 4D surface trajectories to be cleared by the control tower and executed with high precision by the individual flights.

Advanced communication, navigation, and surveillance (CNS) are enabling technologies to realize TBSO. When referring to 4D-trajectory (4DT) operations, it is implicitly assumed that there is already agreement between the Air Navigation Service Provider (ANSP) and the flight deck (FD) on a 4D trajectory to be executed; otherwise the notion of 4D trajectories is meaningless. Full 4D trajectories may imply defining 3D spatial position as a function of time. However, practical concepts involving 4D trajectories define required times of arrival (RTAs) at selected locations along the route, e.g., taxiway intersections, runway intersections, and hold lines. To assure safe operations, it is important to understand the interaction of complete 4D trajectories, including all points between RTA specifications. Accurate knowledge of the 4D trajectories will allow the ANSP to more precisely plan the surface traffic and monitor the operations.

Current-day operations require the ANSP to specify the taxi routes, control the order of merging at intersections or use of runways, and allow the pilots to provide separation visually. To enhance situational awareness of the ANSP, the FAA is introducing new surface surveillance and safety technologies such as Airport Surface Detection Equipment – Model X (ASDE-X), Automatic Dependent Surveillance – Broadcast (ADS-B), Airport Movement Area Safety System (AMASS).
includes research on optimization of airport taxi scheduling
Guidance and Control System (A-SMGCS) [23] concept
Surface Operation Automation Research (SOAR) [7]–
forms the seminal research in surface 4DT operations in
a holistic approach to the problem. SOAR promotes
collaborative automation systems for the tower [11] and the
FD [12]–[14] to enable 4DT operations. With the tower
automation prototype available, the SOAR concept has been
subjected to human-in-the-loop (HITL) evaluation at the
FutureFlight Central (FFC) tower simulator [15] at NASA
Ames Research Center, where some of the human-factors
concerns were studied [16]–[18].
While the SOAR concept examined the surface traffic
control problem as an integrated system involving the
ANSP, the FD, and their associated automation systems and
other enabling technologies, other studies have investigated
individual aspects separately. The Surface Management
System (SMS) [19], developed by NASA in cooperation
with the FAA, is a decision-support tool providing
situational awareness to service providers and NAS users
[20]. Recent NASA research in surface operations include
the development of scheduling and routing algorithms [21],
[22], and human-factors research looking into information
requirements for execution of 4D clearances on the FD.
The EUROCONTROL Advanced Surface Movement
Guidance and Control System (A-SMGCS) [23] concept
includes research on optimization of airport taxi scheduling
[24]. The European Airport Movement Management by A-
SMGCS (EMMA) project defined A-SMGCS operational
requirements [25] for the ANSP and FD, and other
important services such as CNS [26].
The previous SOAR experience in developing the concept
for TBSO has revealed that the flight, while observing RTAs
as constraints along the taxi route, still has many degrees of
freedom in adjusting its state profiles (i.e., position,
velocity, etc. as functions of time) to achieve the timing
constraints. These degrees of freedom in trajectory control
can be exploited to achieve desirable behaviors for the taxi
operations. The previous prototype FD automation applied
the trajectory control freedom to assure passenger comfort
by keeping the accelerations and decelerations within pre-
specified limits. This paper considers the untapped
flexibility for this trajectory design problem to achieve other
additional desirable behaviors, beginning with the
consideration of fuel burn, emissions, and noise. The
findings will benefit future designs of FD automation
systems, as well as tower automation systems which rely on
accurate understanding of the FD’s operational behaviors to
plan efficient and safe operations for the entire surface
traffic.

II. OVERVIEW OF 4D-TRAJECTORY OPERATIONAL CONCEPT
The SOAR concept performs TBSO through collaboration
between tower automation and a FD automation system, known respectively as
Ground-Operation Situation Awareness and Flow Efficiency (GoSAFE) [11] and
Flight-deck Automation for Reliable Ground Operation (FARGO)
[12]–[14]. Figure 1 describes the interactions among the two
automation environments, the human operators, the aircraft
and CNS systems. With GoSAFE issuing the clearances, the
FARGO system provides the Flight-Deck Automation functions to execute the clearances. The SOAR concept is
built upon the following coupled assumptions:
1. GoSAFE can achieve high-precision taxi to meet any
reasonable RTAs along a pre-specified taxi route.
2. GoSAFE counts on FARGO’s precision-taxi capability to
plan efficient and safe surface operations.
Figure 2 shows a general aircraft-control block diagram
involving the FARGO system, which supports both an auto-
taxi mode and a manual mode aided by FARGO automation.
intersections void of nearby traffic. In this case, \( n_e \leq n_p \),
when the 4DT clearance is data-linked to FARGO.

<table>
<thead>
<tr>
<th>Trajectory Types</th>
<th>Trajectory Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planned 4D Route</td>
<td>( [r_{0},r_{p}] \cup [0,1,\ldots,n_p] )</td>
</tr>
<tr>
<td>Cleared 4D Route</td>
<td>( [r_{0},r_{p}] \cup [0,1,\ldots,n] )</td>
</tr>
<tr>
<td>Reference Trajectory</td>
<td>( [r_{0}(t_{0}),r_{p}(t_{p})] \cup [r_{t},r_{t}] )</td>
</tr>
<tr>
<td>Actual Trajectory</td>
<td>( [r_{0}(t_{0}),r_{p}(t_{p})] \cup [r_{t},r_{t}] )</td>
</tr>
<tr>
<td>Measured/Estimated Vehicle State from Navigation</td>
<td>( [r_{0}(t_{0}),r_{p}(t_{p})] \cup [r_{t},r_{t}] )</td>
</tr>
<tr>
<td>Sensed Vehicle State from Surveillance</td>
<td>( [r_{0}(t_{0}),r_{p}(t_{p})] \cup [r_{t},r_{t}] )</td>
</tr>
</tbody>
</table>

**Figure 3. Range of Trajectory Data in 4D-Trajectory Operational Concepts**

From the clearance, FARGO re-creates the cleared 4D route, \( (r_{0}, t_{a}) \), from the data-link message.

The Guidance system generates a reference trajectory that defines position \( r \), velocity \( v \), and acceleration \( a \) as functions of time to meet the crossing constraints. FARGO uses this reference trajectory to control the vehicle’s movement, resulting in the actual trajectory \( (r, v, a) \). The actual trajectory differs from the reference trajectory due to the presence of dynamics, system errors, control effects, and overriding functions such as the self-separation capability of the automation system or human pilot actions. A well-designed Control system would make sure that the actual trajectory is close to the reference trajectory.

Finally, the navigation system measures or estimates the state at specific time instants, \( (r_{n}, v_{n}, t_{a}) \), to feed back the data for control of the aircraft. Similarly, the surveillance system shown in Figure 1 senses the position at less frequent cycles than the navigation system, providing the data \( (r_{a}, v, t_{a}) \).

For advanced surveillance systems such as ADS-B, the surveillance data may also include velocity in addition to position information.

A conformance-monitor function is embedded in the Guidance function of FARGO to evaluate the conformance of the navigation data with respect to the reference trajectory generated by Guidance. The use of these two sets of trajectory for conformance monitoring at the FD (i.e., reference trajectory vs. measured/estimated vehicle state from navigation) is shown in Figure 3, which also shows that conformance monitoring for tower ANSP will be based on comparing surveillance data to the original 4D route (i.e., planned 4D route vs. sensed vehicle state from surveillance), both being lower-fidelity counterparts of data used in FD conformance monitoring.

**III. DEGREES OF FREEDOM IN 4D-TRAJECTORY DESIGN**

The role of the Guidance system is to accept the taxi route specified by the clearance with embedded timing constraints to generate reference 4DT information for the aircraft to track. It takes into consideration airport layout standards [27]. A number of factors go into the computation of the trajectory, including turn radii, hold distances, aircraft performance, passenger comfort, etc. Even when the 3D trajectory is defined with all the turns and straight segments, there still remain many degrees of freedom for defining the velocity profile to meet the timing constraints. The current FARGO prototype imposes additional model behaviors for the velocity profile, hence on the final 4D trajectory. It models movements in intersections with constant speed of reasonable value to control the intersection occupancy time, taking into account dimensions of the intersections and the aircraft itself. This restricts any change in speed to take place only in the segments outside the intersections. All turns are assumed to occur in intersections and hence are modeled with constant speed. Figure 4 is a notional plot to illustrate the speed profile of the 4D trajectory, where the “handles” represent the crossing constraints, and the acceleration and deceleration are restricted to the “legs” of the trajectory.

**Figure 3. Range of Trajectory Data in 4D-Trajectory Operational Concepts**

**Figure 4. Definition of Speed Profile for 4D Trajectory in Current FARGO Implementation**

**Figure 5. Examples of Speed Profiles**

It is evident that the conditions embedded in the 4D routes do not imply unique 4D trajectories: Figure 5 shows a couple of simple examples. The time instants \( t_1, t_2, \) and \( t_3 \) represent three consecutive timing constraints. The black piecewise-constant plot shows the average speed profile.
required to meet these timing constraints. The blue profile of Option A illustrates the approach taken in the current FARGO implementation. A speed is selected for crossing the intersection with a value between the two average speeds on either side of the crossing constraint. The remaining segment between crossing constraints include deceleration and acceleration legs with a constant-speed leg in between.

Option B shows a simpler speed profile that does not assume a constant speed through the intersections. The acceleration and deceleration can be kept small by doing without a constant-speed leg in between. These two simple examples are merely a small sample from a broad spectrum of possibilities. Even if one adopts the approach in Option A, there is still flexibility in selecting the values for the constant speeds, the accelerations, decelerations, and their durations. Furthermore, the speed profile does not even need to be piecewise linear as in these examples.

IV. DESIRABLE PROPERTIES/BEHAVIORS OF SURFACE OPERATIONS

If defining the degrees of freedom in trajectory design is likened to defining the control variables for an optimization problem, then identifying the desired properties/behaviors will be akin to defining the performance metrics. Note that some of the desired properties such as minimizing taxi time are inherent in the TBSO planning function of the tower system, where a 4D trajectory effectively specifies the taxi time. Nevertheless, there still remain certain properties that can be achieved through adjustment of the reference trajectory: e.g., limiting acceleration/deceleration (within human comfort levels), minimizing occupancy time of intersections, minimizing fuel burn, minimizing emission of pollutants and green-house gases (GHG), minimizing noise emission, profile amenable to human manual control (e.g., throttle control carried out in discrete steps). Some of these properties are already built into the TBSO concept. For instance, the SOAR concept tries to reduce taxi time by precisely controlling traffic movement so that taxiing aircraft can cross active runways without slowing down, complying with timing constraints so as not to impact the landing or takeoff operations. The reduction in taxi time proportionally reduces fuel burn and emissions, and the ability to taxi without slowing down would reduce the need for acceleration (hence high throttle settings), further reducing fuel consumption and emissions.

Consultation with a test pilot led to suggestions of certain control behaviors: pilots use throttle and brake as little as possible; most aircraft taxi at idle thrust; brake overheating is not normally a problem; and throttle movements are normally gradual. These suggestions are to be considered for identifying the desirable system-level properties of the TBSO system [28] for designing the 4D trajectory.

V. MODELS AND SIMULATIONS TO SUPPORT TRAJECTORY-DESIGN ASSESSMENT

The FARGO prototype platform [14] is the primary vehicle simulation for studying the execution of 4D trajectories. It was developed around a B-737-type aircraft simulation, which includes a software model of NASA’s Transport System Research Vehicle (TSRV) [12].

For emission modeling, the Emissions and Dispersion Modeling System (EDMS) was identified by the FAA in 1998 as the required model to perform air quality analyses for aviation sources. EDMS models aircraft activity with 6 modes of operation corresponding to the following portions of Landing-Takeoff (LTO) cycle: Approach, Taxi-In, Gate (main engine startup), Taxi-Out, Takeoff, and Climbout. Using EDMS according to these modes of operation is expected to give only first-order effects and may not adequately account for the transient effects of the propulsion system. The transient propulsion effect may become significant when the throttle requires wide ranges of adjustment for acceleration and slowing down. A more detailed engine model—the Commercial Modular Aero-Propulsion System Simulation (C-MAPSS) developed at NASA Glenn Research Center [29]—provides a flexible turbofan engine simulation environment for the study of propulsion transient effects.

For noise modeling, the Integrated Noise Model (INM) is the FAA standard computer model for assessing aircraft noise impacts in the vicinity of airports. It is the required noise assessment tool for airport noise compatibility planning and for environmental assessments and impact statements in compliance with the National Environmental Policy Act [30], [31].

VI. PRELIMINARY ANALYSIS RESULTS

A. Evaluation of Engine Models

An emissions estimation model was constructed for the C-MAPSS simulation output based on equations from Refs. [32] and [33]. The EDMS model uses Base of Aircraft Data (BADA) [34] for aircraft performance measured at four different thrust levels characteristic of different phases of the landing-takeoff cycle. A comparison of the estimation model and the BADA data is shown in Figure 6. The upper left plot shows the fuel flow rates, which are very similar. The three other plots show the Emissions Index (EI) for the three pollutants available from the BADA data: oxides of nitrogen (NOx), carbon monoxide (CO), and unburned hydrocarbons (UHC). Although the results are not always in close agreement, the trends of model are representative of the actual data.

Assessment of trajectory-design options identified will be based on the FARGO simulation and emission models based on EDMS. Discrepancies between the C-MAPSS dynamic model data and the BADA data will provide insight into the
accuracy of the EDMS model in predicting emissions during surface operations.

Figure 6. Comparison of Estimated and BADA Emissions Data

B. Evaluation of Trajectory Designs

This example is taken from DFW, where a flight landing on runway 21R has to cross runways 35C and 35L to get to the terminal. The distance between the runways 35C and 35L is 1200 ft. The aircraft is initially at rest, and the terminal condition is that it must travel 1200 ft in 30 s and have a final velocity of 19 kn. Figure 7 shows on the left the response to one acceleration trajectory command which would meet the criteria, and the corresponding controls on the right. The actual total distance traveled was 1200.2 ft, and the final velocity was 19.36 kn. Based on the ICAO engine database, the emissions were estimated for Pratt & Whitney JT8D-9 engines. Emissions data were interpolated using the thrust level. The total emissions were 57,340 g and the total fuel consumption was 37.86 lb (total of both engines).

A second example is shown in Figure 8, with the acceleration and corresponding control inputs shown in the two graphs. In this case the commanded acceleration is sharper, and there is considerable overshoot as the controller tries to eliminate the tracking errors and uses more throttle. The total distance traveled was 1200.5 ft and the final velocity was 19.55 kn. The total emissions for this run were 59,270 g, and the total fuel consumption was 39.09 lb.

Run 3 is for the same case except that the final time is now 45 s. Here the acceleration is limited to a value that is close to what can be achieved if the engines are limited to about 40% N1, a limit typically specified in flight operations manuals for taxi operations. The acceleration and control histories are shown in Figure 9. The final velocity was 19.26 kn and the distance traveled was 1200.4 ft. The total fuel consumed was 33.08 lb.

The following table summarizes the emissions for the three runs. For the first two runs, although the total fuel consumption is nearly the same in both cases, the second trajectory operates at higher levels of thrust initially, and the production of NOx is disproportionately higher at higher levels of thrust. For the third run that allows a longer taxi time, the fuel and emissions are lower overall, but the CO and UHC emissions are actually higher than in the previous two runs. This is not surprising since the engine runs longer at low RPMs where the EI is lower for NOx and higher for CO and UHC. The total emissions in this table include and are dominated by CO2, which is not considered a pollutant, but a GHG obtained naturally from the combustion process.

<table>
<thead>
<tr>
<th>Run</th>
<th>Total Fuel (lbm)</th>
<th>NOx (g)</th>
<th>CO (g)</th>
<th>UHC (g)</th>
<th>CO2 (g)</th>
<th>Total Emissions (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>37.86</td>
<td>145.6</td>
<td>91.5</td>
<td>20.1</td>
<td>57.083</td>
<td>57,340</td>
</tr>
<tr>
<td>2</td>
<td>39.09</td>
<td>208.5</td>
<td>93.9</td>
<td>20.5</td>
<td>58.947</td>
<td>59,270</td>
</tr>
<tr>
<td>3</td>
<td>33.08</td>
<td>57.8</td>
<td>149.2</td>
<td>33.7</td>
<td>49.878</td>
<td>50,119</td>
</tr>
</tbody>
</table>

VII. CONCLUDING REMARKS

This paper describes a research in progress involving the use of 4D trajectories to support trajectory-based surface operations (TBSO) at highly complex airports. Different trajectory design options are being considered for automation implementation and are being analyzed. The research is expected to lead to a comprehensive set of
reference trajectory design specifications for the flight-deck automation system that will minimize emissions while satisfying the timing constraints for performing TBSO. This set of specifications can be transferred to the tower automation platform to be integrated into its planning and operational functions. Besides clearance handling, the operational functions include those for separation assurance (e.g., conformance monitoring, conflict/incursion detection and avoidance). A well-prepared set of trajectory design specifications will help reduce the model uncertainties required for the trajectories, resulting in more effective operations.

REFERENCES


