Effect of LNAV and VNAV Equipage on Time-Based Scheduling

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This paper evaluates the effect of Lateral NAVigation (LNAV) and Vertical NAVigation (NAV) equipage on the performance on time-based scheduling. The paper relies on two companion papers: (i) the first paper develops a high-fidelity simulations model of LNAV + VNAV, and (ii) the second paper develops a realistic spatio-temporally correlated model of wind uncertainty. Two different Monte Carlo simulation frameworks are used to evaluate the effect of LNAV + VNAV equipage on time-based scheduling. The first Monte Carlo simulation framework is used to evaluate the time-of-arrival uncertainty for flights equipped with LNAV + VNAV capability. This Monte Carlo simulation uses a point-mass simulation model of the aircraft equipped with LNAV + VNAV and flying through spatio-temporally correlated wind uncertainty fields. The second Monte Carlo simulation evaluates the effect of LNAV + VNAV equipage on the performance of time-based scheduling. NASA’s Stochastic Terminal Area Scheduling and Simulation (STASS) software is used for time-based scheduling and terminal area traffic simulations. Terminal-area traffic Monte Carlo simulations are conducted for 1.0x, 1.5x, and 2.0x demand ratio at San Francisco International Airport (SFO), Los Angeles International Airport (LAX), and Dallas Fort Worth International Airport (DFW). Results illustrating the effect of LNAV + VNAV equipage level (0\%, 25\%, 50\%, and 75\%) on delay, throughput, and the number of separation violations are presented in the paper.

I. Introduction

NASA and the FAA have been involved in extensive efforts to develop advanced concepts, technologies, and procedures for the Next Generation Air Transportation System (NextGen)\textsuperscript{1}. The objective of these research efforts has been to improve the capacity, efficiency, and safety in the next-generation National Airspace System (NAS). Improvements can come in the form of more accurate and autonomous onboard navigational capabilities based on the Global Positioning System, more accurate surveillance capabilities such as Automatic Dependent Surveillance-Broadcast, advanced communication capabilities such as datalink, improved vehicle designs, and improved air-traffic operations realized through advanced automation systems. A significant portion of the NextGen research is aimed at (i) developing ground-side automation systems to assist controllers in strategic planning operations, (ii) developing controller decision support tools to separate and space the traffic, and (iii) developing flight-deck-side automation to assist pilots in accomplishing airborne merging and spacing operations.

Reference 2 describes a concept for future high-density terminal air traffic operations that has been developed by the Airspace Super Density Operations (ASDO) researchers at NASA Ames Research Center. The concept described in Ref. 2 includes five core capabilities: 1) Extended Terminal Area Routing, 2) Precision Scheduling Along Routes, 3) Merging and Spacing, 4) Tactical Separation, and 5) Off-Nominal Recovery. The first two capabilities are strategic planning tools and the remaining three are tactical decision support tools.

Successful implementation of precision scheduling requires an understanding of the following:

- The range of flight times feasible for an aircraft to transit between two points along its flight path (e.g., Top of Descent to a Meterfix & Meterfix to Runway)
- The accuracy with which an aircraft can realize a Scheduled Time of Arrival (STA)
- The accuracy with which an aircraft can maintain self-separation with respect to a leading aircraft?

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The feasible flight time depends on the following:

- Aircraft performance characteristics
- Cruise and descent speeds selected by the Flight Management System (FMS)
- Terminal area route geometry
- Atmospheric conditions such as temperature and winds

The Time-of-Arrival (TOA) accuracy and self-separation accuracy depend on the following:

- Uncertainty associated with the atmospheric predictions.
- Advisories from ground-side controllers assisted by automation tools such as Controller Managed Spacing (CMS).
- Current-day and NextGen FMS automation capabilities which are the focus of current research.

Current-day and NextGen FMS capabilities that affect the TOA accuracy at a Meterfix or runway are listed below:

1) Lateral NAVigation (LNAV) & Vertical NAVigation (VNAV) features of that enable 3D-path tracking capability.
2) Required Time-of-Arrival (RTA) feature of FMS that enables an explicit TOA specification at waypoints such as the Meterfix and runway.
3) Interval Management (IM) tools that enable the capability to maintain spatial and temporal spacing with another aircraft.
4) 4Dimensional FMS (4DFMS) capability that enables full 4D-trajectory tracking.

The objective of the research in this paper is to evaluate the impact of LNAV + VNAV equipage on the performance of time-based scheduling in the terminal airspace, specifically for arrival flights. Section II introduces overall framework to realize the afore mentioned objective. Section III describes the time-based scheduling concept. Section IV presents the TOA uncertainty results associated with LNAV + VNAV capability. Section V presents the predicted delay and throughput benefits for SFO, LAX, and DFW airports as a function of LNAV+VNAV equipage level and demand.

II. Introduction

The overall approach to evaluate the effect of LNAV + VNAV equipage on time-based scheduling can be split into two sub-objectives:

- **Objective 1**: Characterizing the TOA accuracy of a flight equipped with LNAV + VNAV at the Meterfix and runway. This objective is pursued in detail in Reference 33.
- **Objective 2**: Characterizing the effect of equipping arrival flights with LNAV + VNAV on delay, throughput, and separation violation metrics at different airports.

Figure 1 depicts a dual Monte Carlo simulation approach for evaluating the above mentioned objectives. The first Monte Carlo simulation uses a high-fidelity simulation of a single aircraft equipped with LNAV + VNAV capability. High-fidelity aircraft simulation in the context of the current work includes point-mass simulation of an aircraft - with 7 states $x, y, h$, speed, heading, flight path angle, and mass of the aircraft; auto-pilot models; engine lag model; and an atmospheric uncertainty model. The first Monte Carlo simulation evaluates the TOA uncertainty of an aircraft equipped with LNAV + VNAV subjected to realistic atmospheric uncertainties. The simulation consists of the following components: (i) NextGen FMS Capability models, (ii) aircraft simulation, (iii) atmospheric uncertainty models, and (iv) terminal airspace route data. Reference 33 provides a detailed description of this first Monte-Carlo simulation.

The second Monte Carlo simulation uses a time-based scheduling software and a lower fidelity terminal area traffic simulation. The TOA uncertainty models resulting from the first Monte Carlo simulation framework are treated as inputs to the time-based scheduler. The current research uses Stochastic Terminal Area Scheduling Software (STASS) developed at NASA Ames Research Center. STASS serves the dual purposes of time-based scheduling and terminal-area traffic simulation. The outputs from the STASS scheduler are the STAs for each flight in the demand data set. The robustness of the STASS schedule when subject to the TOA uncertainty models is tested using another set of terminal-area traffic Monte Carlo simulations also by STASS. Outputs from this second set of Monte-Carlo simulations are the statistics of average delay, throughput, and number of separation violations.
III. Time-Based Scheduling

Time-based scheduling refers to the process of sequencing and scheduling flights at the Meterfix and runway in order to maximize throughput, or minimize delay while respecting the inter-aircraft separation constraints. The Traffic Management Advisor (TMA)\textsuperscript{24} is one of earliest scheduling tools developed at NASA Ames Research Center. The TMA supports en route controllers and managers with scheduling, spacing, and arrival flow management and is currently deployed at multiple Air Route Traffic Control Centers. The TMA uses a timeline graphical user interface to display schedule and sequence constraints at the traffic management position. Terminal Area Precision Scheduling and Spacing (TAPSS)\textsuperscript{25,26} is an integrated set of trajectory-based automation tools providing precision scheduling, sequencing, and controller merging and spacing functions. It is a strategic and tactical planning tool that provides Traffic Management Coordinators, En Route and Terminal Radar Approach Control air traffic controllers with the ability to efficiently optimize the arrival capacity of a demand-impacted airport, while simultaneously enabling fuel-efficient descent procedures. The TAPSS system consists of four-dimensional trajectory prediction, arrival runway balancing, aircraft separation constraint-based scheduling, traffic flow visualization, and trajectory-based advisories, to assist controllers in efficient metering, sequencing, and spacing.

Among other terminal area scheduling research, Reference 27 proposed a decision support tool for high-density departure and arrival traffic management. Saraf et. al\textsuperscript{28} developed a dynamic scheduling algorithm using optimization techniques. Capozzi et al.\textsuperscript{29} developed a mixed-integer linear programming formulation for optimal routing and scheduling of Metroplex operations. In Reference 30 Saraf et al. compare different scheduling algorithms for Metroplex operations.

The terminal-area scheduling tool used in the current research is STASS. It is a massively parallel advanced scheduling software created at NASA Ames Research Center. STASS was designed as a time-based scheduling simulation tool that models aircraft arrivals in the terminal area. The scheduling is performed in two steps using (1) the Center Scheduler to schedule aircraft from the freeze horizon to the meter fixes and runways and (2) the TRACON Scheduler to schedule aircraft to the runways upon their arrival at the meter fixes. Uncertainty in arrival times is modeled at the freeze horizon, meter fixes, and runways. STASS uses two types of constraints: inter-aircraft
separation, and transit time bounds. The required inter-aircraft spatial separations, mandated by the FAA, are converted in STASS to time constraints using nominal aircraft speeds at the meter fix and runway. Transit time constraints are derived from the minimum and maximum transit times for aircraft traveling through the center and TRACON airspaces. Advanced versions of STASS consider time-advance and constrained position shift to realize better performance. Figure 2 shows a schematic of the terminal area scheduling problem for arrival flights. Scheduling and sequencing is done at two points: (i) Meterfix (indicated by MF in Figure 2) and (ii) Runway Threshold (indicated by RT in Figure 2). The inputs to the scheduler are typically: (i) list of flights including their aircraft type, wake classification category and engine type, (ii) TOA at the schedule freeze horizon (19 minutes to the Meterfix), (iii) TOA uncertainty at the meterfix, (iv) transit-time from Meterfix to runway (all combinations permitted by the runway configuration), and (v) transit-time uncertainty. Figure 3 further illustrates the TOA and transit-time uncertainty.

Figure 2. Schematic of the Terminal Area Scheduling Problem

Figure 3. Time-of-Arrival and Transit-Time Uncertainty
The transit-time matrix file consists of the following pieces of information: (i) number of feeder fixes and their name, (ii) number of runways and their names, (iii) transit-time from each feeder fix to applicable runways characterized as a function of the engine type. Three engine types are considered: (i) Jet, (ii) Turboprop, and (iii) Piston.

The following aircraft data is required by STASS: (i) tail number, (ii) flight id, (iii) aircraft type, (iv) appearance probability, (v) feeder fix name, (vi) engine type, (vii) wake vortex category, and (viii) TOA at freeze horizon. The aircraft data set is randomly segregated by STASS into two groups one unequipped and the other equipped which in the current paper refers to LNAV/VNAV capability.

STASS also uses additional parametric settings that specify the temporal buffer to be used both at the Meterfix and runway. These buffers are required to accommodate the uncertainty associated with the times-of-arrival. These uncertainties are a function of the aircraft equipage. STASS permits the use of two different equipage levels. In this research equipped flights are treated as those with LNAV + VNAV equipage. Unequipped flights are those without any of the following capabilities: LNAV, VNAV, RTA, IM, and 4DFMS.

**IV. Time-of-Arrival Uncertainty Models**

The current section describes the methodology used to estimate the TOA uncertainty associated with LNAV + VNAV capability. Reference 33 provides a detailed description and results from the Monte-Carlo simulation to characterize the TOA uncertainty associated with LNAV/VNAV flights. A summary of the overall approach and key results are presented here for the benefit of the reader.

**A. LNAV + VNAV Closed Loop Simulation**

Figure 4 shows the closed-loop simulation used to evaluate the TOA performance of the LNAV + VNAV capability.

![Diagram of LNAV + VNAV Closed Loop Simulation](attachment:image.png)

**Figure 4. Closed Loop Simulation Setup of LNAV+VNAV**

The simulation consists of a reference trajectory generator which generates the horizontal and vertical plane reference paths. Together the horizontal and vertical plane reference paths constitute the 3D-reference path. Reference 32 describes the algorithms used for reference trajectory synthesis. The LNAV and VNAV modules take in as input the horizontal and vertical reference paths and compare it with the navigation state of the aircraft.
Depending on the observed deviations between the 3D-reference paths and the current state of the aircraft LNAV and VNAV generate corrective actions in the form of a bank angle command and lift-coefficient command respectively. Actual VNAV is expected to generate either pitch-attitude command or an angle-of-attack command. However, developing such a model would require an aerodynamic model more sophisticated than the Base of Aircraft DAtabase BADA drag-polars assumed under the current research. It should be noted all aircraft performance data used in this paper is based on BADA 3.9.

Whereas, LNAV and VNAV track the 3D-reference path the thrust control module and spoiler control modules maintain the reference airspeed within limits without any regard to groundspeed or the TOA. Thrust and drag commands are generated depending on the observed deviation between the reference and the actual airspeeds of the aircraft. Reference 33 describes the algorithms used for LNAV, VNAV, thrust control, and spoiler control.

In an actual aircraft the bank angle, lift coefficient, and thrust commands are realized by the auto-pilot and engine. This paper uses second-order response models for bank angle and pitch axis auto-pilot models. A first-order model is used to model the lag from the throttle. The outputs from the bank angle auto-pilot and engine models are input to an aircraft point mass simulation. The lift coefficient and the spoiler drag command are processed through the BADA drag-polars and a spoiler aerodynamic model to produce the aerodynamic lift and drag forces acting on the aircraft. The lift and drag aerodynamic forces are in turn used to drive the point-mass simulation model. Detailed equations relating to the simulation are presented in a companion paper (see Reference 33).

B. Wind Uncertainty

In addition to the aerodynamic forces, thrust, and bank angle the point-mass simulation also takes in as inputs the North and East wind components of wind. In this paper the wind is modeled as the sum of two components: (i) deterministic forecast component and (ii) a random forecast error component. The random forecast error represents the uncertainty in the wind. This paper uses a realistic wind uncertainty model that is based on the observed deviations between forecast atmospheric data and actual atmospheric data. It is assumed that the FMS uses forecast atmospheric data. National Oceanic and Atmosphere Administration's (NOAA’s) 1hr RAPid Refresh Data (RAP) is used as the wind forecast. Actual wind data is extracted from Aircraft Communications Addressing and Reporting System (ACARS) data which in turn is obtained from Meteorological Assimilation Data Ingest System (MADIS).

RAP provides North and East components of wind at 13 km horizontal plane resolution, and 50 vertical levels. The forecasts are available 1 through 18 hours in advance. A bi-linear interpolation scheme is used to generate wind data for arbitrary latitude, longitude, and altitude specification. The ACARS data is actual aircraft recorded wind data and is considered true wind for the purpose of characterizing the wind forecast errors. ACARS also provides the North and East components of the wind. However, this data is only available at spatial locations along a flight’s path.

Figure 5 shows a block diagram of the wind-uncertainty characterization framework.

![Figure 5. Wind Uncertainty Characterization Framework](image)

Overall, the wind uncertainty model used in the current paper has the following features:

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• Wind is modeled as a function of latitude, longitude, altitude, and time.
• Wind uncertainty is characterized by the standard deviation of the errors as a function of altitude. The standard deviation is observed to increase with altitude.
• The wind errors are correlated both spatially and temporally.
• A more detailed description of this is available in an accompanying paper (see Reference 34).

C. Monte Carlo Simulation
The previous sub-sections described the closed loop simulation environment used to evaluate the LNAV + VNAV capabilities and the wind-uncertainty model. This section describes the Monte Carlo simulation framework used to establish the TOA uncertainty for aircraft equipped with LNAV/VNAV capability and subject to wind uncertainties. The Monte Carlo simulations are conducted in two stages: (i) from Freeze Horizon (about 120nmi away from the Meterfix) to Meterfix, and (ii) from the Meterfix to the runway. Each Monte Carlo simulation uses the same aircraft, flying along the same route. The aircraft uses the same reference trajectory and experiences the same deterministic wind forecast component. However, each simulation experiences a different random forecast error component.

The reference trajectory used in the simulations is generated for a A320 aircraft flying along the BIGSUR route at SFO. The Meterfix is chosen as the BOLDR waypoint along the route, and the runway is chosen as the 28R runway. Figure 6 show the standard deviation of the errors as a function of path length from Freeze Horizon to Meterfix. In Figure 6 the initial path length equal to zero represents the Freeze Horizon and final path length close to 120nmi represents the Meterfix. It can be inferred from this figure that the uncertainty in TOA at the Meterfix for this aircraft example is 6.5seconds.

Figure 7 shows standard deviation of the errors as a function of path length from Meterfix to Runway. In Figure 7 the initial path length equal to zero represents the Meterfix and final path length close to 30nmi represents the Runway. It can be inferred from this figure that the uncertainty in TOA at the Runway for this aircraft example is 3.75seconds.

Figure 6. STD of TOA Errors from Freeze Horizon to Meterfix
Figure 7. STD of TOA Errors from Meterfix to Runway

V. Time-Based Scheduling Simulation Results
Details of the time-based scheduling experiment conducted using STASS at SFO, LAX, and DFW airports are presented in this section.

The following simulation scenarios are considered:
• Demand Ratios: 1.0x, 1.5x, 2.0x
• Equipage Fractions: 0, 25%, 50%, and 75%
• Number of Monte-Carlo Iterations: 500
• Outputs: Average Delay, Makespan, and Runway Separation Violations

A total of 12 Monte-Carlo simulation scenarios (3 Demand Ratios x 4 Equipage Ratios) are chosen to evaluate the impact of LNAV/VNAV equipage on time-based scheduling at each of the three airports SFO, LAX, and DFW.
Each Monte-Carlo simulation represents a 4Hr traffic scenario (at 1.0x demand). Each Monte-Carlo scenario involves 500 simulations of the terminal area traffic using randomly generated times-of-arrival and transit-times.

Table 1 shows STASS parametric settings related to time-of-arrival accuracy resulting from LNAV + VNAV (equipped aircraft) and unequipped aircraft. It also shows the spacing buffers used for equipped and unequipped aircraft. The TOA standard deviation of the equipped (LNAV/VNAV) aircraft are based on Figure 6 and Figure 7 in Section IV. The LAX terminal area routes are longer than the SFO routes. Hence, the TOA uncertainty at the Runway for LAX is chosen (by extrapolation) slightly higher than that of the SFO routes. The TOA standard deviations for unequipped aircraft are assumed to be slightly higher than the LNAV/VNAV equipped aircraft. This is an important assumption because the benefits expected from equipped aircraft depend strongly on the TOA uncertainty values relative to the unequipped aircraft.

Table 1. STASS Parametric Settings

<table>
<thead>
<tr>
<th></th>
<th>SFO, DFW</th>
<th>LAX</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Time-of-Arrival</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard Deviation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>@ Meterfix</td>
<td>10</td>
<td>7.5</td>
</tr>
<tr>
<td>Time-of-Arrival</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard Deviation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>@ Runway</td>
<td>8</td>
<td>4</td>
</tr>
<tr>
<td>Spacing Buffer</td>
<td></td>
<td></td>
</tr>
<tr>
<td>@ Meterfix</td>
<td>10</td>
<td>7.5</td>
</tr>
<tr>
<td>Spacing Buffer</td>
<td></td>
<td></td>
</tr>
<tr>
<td>@ Runway</td>
<td>8</td>
<td>4</td>
</tr>
</tbody>
</table>

A. SFO Time-Based Scheduling Results

Figure 8 shows the TRACON route model for San Francisco used in current simulations. Five Standard Terminal Arrival Routes (STARs) and one arrival runway 28R are used for this experiment.
Table 2 labels the five different routes and their Meterfixes.

<table>
<thead>
<tr>
<th>S. No</th>
<th>Route Name</th>
<th>Meterfix</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>BIGSUR</td>
<td>BOLDR</td>
</tr>
<tr>
<td>2</td>
<td>MODESTO</td>
<td>CEDES</td>
</tr>
<tr>
<td>3</td>
<td>PIRAT</td>
<td>HOMKA</td>
</tr>
<tr>
<td>4</td>
<td>GOLDN</td>
<td>LOZIT</td>
</tr>
<tr>
<td>5</td>
<td>RISTI</td>
<td>CEDES</td>
</tr>
</tbody>
</table>

Table 3 lists a synopsis of the benefits resulting from equipping 75% of the flights with LNAV/VNAV capability at SFO. The benefits are with respect to 0% LNAV/VNAV equipage scenario. It should be noted that the results are rounded to the nearest integer value.

<table>
<thead>
<tr>
<th>Demand Ratio</th>
<th>No. of Flights</th>
<th>Change in Avg. Delay</th>
<th>% Change in Makespan</th>
<th>% Change in Separation Viols.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0x</td>
<td>112</td>
<td>2.85 seconds</td>
<td>-12%</td>
<td>0%</td>
</tr>
<tr>
<td>1.5x</td>
<td>168</td>
<td>48 seconds</td>
<td>-25%</td>
<td>0%</td>
</tr>
<tr>
<td>2.0x</td>
<td>224</td>
<td>210 seconds</td>
<td>-17%</td>
<td>-3%</td>
</tr>
</tbody>
</table>

Whereas Table 3 lists the benefits for 75% equipage ratio the figures below illustrate the benefits for different equipage levels between 0%-75%. Figure 9, Figure 11, and Figure 13 illustrate the effect of LNAV/VNAV equipage on the average delay at 1.0x, 1.5x, and 2.0x demand ratios respectively. The x-axis represents the fraction of flights.
equipped with LNAV/VNAV capability. Figure 10, Figure 12, and Figure 14 illustrate the effect of LNAV/VNAV equipage on Makespan at 1.0x, 1.5x, and 2.0x demand ratios respectively. Figure 15, Figure 16, Figure 17 illustrate the effect of LNAV/VNAV equipage on Runway Separation Violations at 1.0x, 1.5x, and 2.0x demand ratios respectively.
Figure 13. Average Delay at 2.0x Demand

Figure 14. Makespan at 2.0x Demand

Figure 15. Separation Violations at 1.0x Demand

Figure 16. Separation Violations at 1.5x Demand

Figure 17. Separation Violations at 2.0x Demand
B. LAX Time-Based Scheduling Results

Figure 18 shows the LAX terminal airspace route geometry used for the current experiment. Six STARs and two arrival runways 25L and 24R are used in this experiment.

![Figure 18. LAX TRACON Route Geometry](image)

Table 4 shows the Meterfixes chosen along each of the six arrival routes in Figure 18.

<table>
<thead>
<tr>
<th>S. No</th>
<th>Route Name</th>
<th>Meterfix</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>RIIVR</td>
<td>GRAMM</td>
</tr>
<tr>
<td>2</td>
<td>SEAVU</td>
<td>KONZL</td>
</tr>
<tr>
<td>3</td>
<td>SADEE</td>
<td>PIRUE, VTU</td>
</tr>
<tr>
<td>4</td>
<td>SHIVE</td>
<td>SHIVE</td>
</tr>
<tr>
<td>5</td>
<td>KIMMO</td>
<td>LHS</td>
</tr>
<tr>
<td>6</td>
<td>LEENA</td>
<td>SXC</td>
</tr>
</tbody>
</table>
Table 5 lists a synopsis of the benefits resulting from equipping 75% of the flights with LNAV/VNAV capability at LAX. The benefits are with respect to 0% LNAV/VNAV equipage scenario. It should be noted that the results are rounded to the nearest integer value.

Table 5. Synopsis of Expected Benefits from 75% LNAV/VNAV Equipage at LAX

<table>
<thead>
<tr>
<th>Demand Ratio</th>
<th>No. of Flights</th>
<th>Change in Avg. Delay</th>
<th>% Change in Makespan</th>
<th>% Change in Separation Viols.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0x</td>
<td>182</td>
<td>3.6 seconds</td>
<td>-14%</td>
<td>0%</td>
</tr>
<tr>
<td>1.5x</td>
<td>273</td>
<td>33 seconds</td>
<td>-19%</td>
<td>0%</td>
</tr>
<tr>
<td>2.0x</td>
<td>364</td>
<td>156 seconds</td>
<td>-20%</td>
<td>-3%</td>
</tr>
</tbody>
</table>

Figure 19, Figure 21, and Figure 23 illustrate the effect of LNAV/VNAV equipage on Average Delay at LAX for 1.0x, 1.5x, and 2.0x demand ratios respectively. Figure 20, Figure 22, and Figure 24 illustrate the effect of LNAV/VNAV equipage on Makespan at LAX for 1.0x, 1.5x, and 2.0x demand ratios respectively. Figure 25, Figure 26, and Figure 27 illustrate the effect of LNAV/VNAV equipage on Runway Separation Violations at LAX for 1.0x, 1.5x, and 2.0x demand ratios respectively.
Figure 23. Average Delay at 2.0x Demand
Figure 24. Makespan at 2.0x Demand
Figure 25. Separation Violation at 1.0x Demand
Figure 26. Separation Violations at 1.5x Demand
Figure 27. Separation Violations at 2.0x Demand
C. DFW Time-Based Scheduling Results

Figure 28 shows the DFW TRACON route model used in this paper. Three arrival Meterfixes and four runways are used in this experiment.

Table 6 lists a synopsis of the benefits resulting from equipping 75% of the flights with LNAV/VNAV capability at DFW. The benefits are with respect to 0% LNAV/VNAV equipage scenario. It should be noted that the results are rounded to the nearest integer value.

<table>
<thead>
<tr>
<th>Demand Ratio</th>
<th>No. of Flights</th>
<th>Change in Avg. Delay</th>
<th>% Change in Makespan</th>
<th>% Change in Separation Viols.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Actual</td>
<td>%</td>
<td></td>
</tr>
<tr>
<td>1.0x</td>
<td>276</td>
<td>7.5 seconds</td>
<td>-13%</td>
<td>0%</td>
</tr>
<tr>
<td>1.5x</td>
<td>414</td>
<td>170 seconds</td>
<td>-15%</td>
<td>-2%</td>
</tr>
<tr>
<td>2.0x</td>
<td>552</td>
<td>280 seconds</td>
<td>-9%</td>
<td>-3%</td>
</tr>
</tbody>
</table>

Figure 29, Figure 31, and Figure 33 illustrate the effect of LNAV/VNAV equipage on Average Delay at DFW for 1.0x, 1.5x, and 2.0x demand ratios respectively. Figure 30, Figure 32, and Figure 34 illustrate the effect of LNAV/VNAV equipage on Makespan at DFW for 1.0x, 1.5x, and 2.0x demand ratios respectively. Figure 35, Figure 36, and Figure 37 illustrate the effect of LNAV/VNAV equipage on Runway Separation Violations at DFW for 1.0x, 1.5x, and 2.0x demand ratios respectively.
Figure 29. Average Delay at 1.0x Demand

Figure 30. Makespan at 1.0x Demand

Figure 31. Average Delay at 1.5x Demand

Figure 32. Makespan at 1.5x Demand

Figure 33. Average Delay at 2.0x Demand

Figure 34. Makespan at 2.0x Demand
Figure 35. Separation Violations at 1.0x Demand

Figure 36. Separation Violations at 1.5x Demand

Figure 37. Separation Violations at 2.0x Demand

D. Summary
Table 7 summarizes all the STASS Monte-Carlo simulation results presented in the previous sections.

<table>
<thead>
<tr>
<th>Airport</th>
<th>Demand Ratio</th>
<th>No. of Flights</th>
<th>Change in Avg. Delay Actual</th>
<th>Change in % Makespan</th>
<th>Change in % Runway Separation Violations</th>
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</thead>
<tbody>
<tr>
<td>SFO</td>
<td>1.0x</td>
<td>112</td>
<td>2.85 seconds -12%</td>
<td>0%</td>
<td>-11%</td>
</tr>
<tr>
<td>SFO</td>
<td>1.5x</td>
<td>168</td>
<td>48 seconds -25%</td>
<td>0%</td>
<td>-6%</td>
</tr>
<tr>
<td>SFO</td>
<td>2.0x</td>
<td>224</td>
<td>210 seconds -17%</td>
<td>-3%</td>
<td>-1%</td>
</tr>
<tr>
<td>LAX</td>
<td>1.0x</td>
<td>182</td>
<td>3.6 seconds -14%</td>
<td>0%</td>
<td>-19%</td>
</tr>
<tr>
<td>LAX</td>
<td>1.5x</td>
<td>273</td>
<td>33 seconds -19%</td>
<td>0%</td>
<td>-12%</td>
</tr>
<tr>
<td>LAX</td>
<td>2.0x</td>
<td>364</td>
<td>156 seconds -20%</td>
<td>-3%</td>
<td>-10%</td>
</tr>
<tr>
<td>DFW</td>
<td>1.0x</td>
<td>276</td>
<td>7.5 seconds -13%</td>
<td>0%</td>
<td>-16%</td>
</tr>
<tr>
<td>DFW</td>
<td>1.5x</td>
<td>414</td>
<td>170 seconds -15%</td>
<td>-2%</td>
<td>-9%</td>
</tr>
<tr>
<td>DFW</td>
<td>2.0x</td>
<td>552</td>
<td>280 seconds -9%</td>
<td>-3%</td>
<td>-9%</td>
</tr>
</tbody>
</table>

In summary this paper has illustrated that increasing the ratio of high-equipage aircraft will result in reduced TOA uncertainty, which in turn will lead to delay reduction benefits. The benefits are not uniform and seem to differ

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for different airports and demand ratios. The above benefits portray a beneficial impact of LNAV/VNAV Capability on Time-Based Scheduling especially at higher demand ratios. However, it is important to recognize the assumptions of the benefits evaluation process. Some of the assumptions and caveats are listed below:

- **Concept:**
  - The overall concept assumes the ability to predict the aircraft's TOA in the absence of uncertainty. For this purpose it is important to know the weight, cruise altitude, cruise CAS, descent Mach, and descent CAS of the aircraft. Datalink capability may be required for transmitting this information from the flight-deck to the ground-side.
  - It is assumed that the aircraft’s reference trajectory is based on a 1hour RAP forecast. For long duration flights this might require some form of communication from the Airline Operations Center to receive these forecasts before the initiation of descents.

- **Uncertainty:**
  - The TOA uncertainty is based on Monte-Carlo simulation of one aircraft (A320 flying along BIGSUR Route at SFO). Further Monte-Carlo simulations need to be conducted to better evaluate this uncertainty for a wider range of aircraft, routes, and wind conditions.
  - TOA uncertainty is currently estimated along one route at SFO using one wind uncertainty model generated using 15 days of ACARS and RAP data. In case, the uncertainty is not constant over the entire year the TOA uncertainty as well as the NextGen Capability benefits will vary.
  - Whereas the TOA uncertainty associated with flights equipped with NextGen Capabilities has been rigorously estimated, the TOA uncertainty associated with unequipped aircraft is not known. In this work it was assumed that the TOA uncertainty associated with unequipped aircraft is slightly higher than those aircraft equipped with LNAV/VNAV capability. This is a crucial assumption with significant impact on the results obtained.

- **Simulation:**
  - The STASS simulation environment uses a single transit-time for all flights along a route. In reality the transit-time depends on the aircraft type and the descent speeds.
  - The STASS simulation environment uses a single TOA uncertainty model for all flights. The actual TOA uncertainty depends on the length of routes and distance from Meterfix to Runway which could vary for different routes. The longer the distance the higher the uncertainty.

**Conclusion**

The paper presents a rigorous framework for evaluating the benefits of LNAV + VNAV equipage on the performance of time-based scheduling. Preliminary results indicate average-delay reduction benefits ranging from 3seconds to 280seconds. These benefits correspond to a fleet-wide LNAV+VNAV equipage level of 75%. The benefits are more relevant for higher demand ratios (1.5x and 2.0x) than the current 1.0x demand ratio. The effect of LNAV/VNAV equipage on throughput seems very modest. The number of separation violations seem to reduce and overall benefit from LNAV/VNAV equipage. The results are based on a high-fidelity LNAV + VNAV model developed in house and also a realistic wind uncertainty model. There exists some scope for refinement of these models. Whereas the TOA uncertainty associated with flights equipped with NextGen Capabilities has been rigorously estimated, the TOA uncertainty associated with unequipped aircraft is not known. In this work it was assumed that the TOA uncertainty associated with unequipped aircraft is slightly higher than those aircraft equipped with LNAV/VNAV capability. This is a crucial assumption with significant impact on the results obtained. However, the paper establishes a realistic expectation of benefits from LNAV/VNAV equipage.

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