

SURFACE MAP TRAFFIC INTENT DISPLAYS AND NET-CENTRIC DATA-LINK COMMUNICATIONS FOR NEXTGEN

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Abstract

By 2025, U.S. air traffic is predicted to increase three fold and may strain the current air traffic management system, which may not be able to accommodate this growth. In response to this challenge, a revolutionary new concept has been proposed for U.S. aviation operations, termed the Next Generation Air Transportation System or “NextGen”. Many key capabilities are being identified to enable NextGen, including the use of data-link communications. Because NextGen represents a radically different approach to air traffic management and requires a dramatic shift in the tasks, roles, and responsibilities for the flight deck, there are numerous research issues and challenges that must be overcome to ensure a safe, sustainable air transportation system. Flight deck display and crew-vehicle interaction concepts are being developed that proactively investigate and overcome potential technology and safety barriers that might otherwise constrain the full realization of NextGen. The paper describes simulation research, conducted at National Aeronautics and Space Administration (NASA) Langley Research Center, examining data-link communications and traffic intent data during envisioned four-dimensional trajectory (4DT)-based and equivalent visual (EV) surface operations. Overall, the results suggest that controller pilot data-link communications (CPDLC) with the use of mandatory pilot read-back of all clearances significantly enhanced situation awareness for 4DT and EV surface operations. The depiction of graphical traffic state and intent information on the surface map display further enhanced off-nominal detection and pilot qualitative reports of safety and awareness.

Introduction

A key enabler of envisioned operations under NextGen and its “net-centric” environment is data-link communications and a voice-by-exception airspace environment. The research literature

suggests that data-link may improve one source of miscommunications – the inability to get the message from one party to the other – but it does not necessarily address the rest of the communications process – i.e., whether the message was understood and whether it accurately conveyed the speaker’s intent. In a NextGen environment – with closer spacing and more pilot responsibility for separation – increased head-down time and increased workload could significantly reduce safety margins. Concerns have also been raised in a net-centric data-link environment on the need or modality change effects associated with the presence or absence of “party-line” communications [1] – [15]. While past work notes its criticality, these works also show that the “party-line” information influence is dependent upon crew resources, communication, and workload. These influences could possibly be impacted by generational versions of NextGen – for example, the potential that ADS-B “in” capability, possibly augmented with intent data, might provide a suitable alternative to party-line voice communications. Because NextGen represents a radically different approach to air traffic management, NASA is addressing numerous research issues and challenges that must be overcome to ensure a safe, sustainable air transportation system.

In this study, research specifically addressed: 1) safety concerns regarding changes in communication modalities and 2) the impact of emerging NextGen operational concepts and possible crew-vehicle interface mitigations to enable operations, such as equivalent visual operations (EVO), or four-dimensional trajectory (4DT)-based air and surface operations [16]-[17].

Data-Link Communication

The challenge for NextGen is to replicate the strengths and advantages of the previous communication method (i.e., voice) while bringing

to bear the benefits of the new. NASA is conducting a research portfolio which strives to meet this goal. Part of this work targets flight crew assessment of the modality change effects associated with data-link operations, the impact of party-line information changes, and potential mitigating or confounding factors for NextGen operations. Past research has demonstrated that the efficacy of party-line information is dependent upon crew resources, communication, and workload. These influences are undoubtedly also impacted by auditory demands and other visual data available to the flight crew. In particular, what potential exists in the information available by use of ADS-B “in” capability, with traffic intent data? Could the visual display of data-link information and associated navigation and intent data serve to replace voice (voice-by-exception) for routine communications and compensate for the potential impacts of party-line information loss or inherent latencies in managing mixed voice and data pilot-Air Traffic Control (ATC) communications with Controller-Pilot Data Link Communications (CPDLC).

To achieve the NextGen vision, research is necessary to proactively investigate technology which may overcome potential safety barriers that would otherwise constrain surface traffic optimization, maximum runway capacity through reduced runway occupancy time, simultaneous single runway operations, and 4DT and equivalent visual operations, among others [16]-[17]. These safety objectives were the focus of a research study conducted at NASA Langley Research Center that attempted to examine a set of safety issues associated with data-link communications with surface operations being envisioned for NextGen.

The data-link communication experiment evaluated how data-link implementations and mixed-modality communication (i.e., voice and data-link) impact crew decision-making, workload, situation awareness, and crew coordination during operational situations conducted under envisioned 4DT EVO NextGen operational concepts. This paper specifically describes the off-nominal performance aspects of this research and 4DT taxi performance. Off-nominal scenarios (e.g., incorrect clearances, pilot blunders/errors, and data-link transmission errors) were unexpectedly introduced

as critical tests of the robustness and safety of the operations.

Traffic Intent Display

A second experiment examined various levels of traffic intent information on a surface map display. In this experiment, intent is operationally defined as aircraft state and assigned 4DT route guidance information. The experiment assessed whether intent information may aid or be required in NextGen operations and to what extent or what instantiations might be required. The paper describes the off-nominal detection results only. Off-nominal event testing was included, testing surface conflicts and taxi blunders, incorrect data-link clearances, detection of non-participating objects, and runway incursions.

METHOD

Research Flight Crews

Twenty-four pilots served as participants for the research, representing twelve flight crews. Each flight crew flew for a major U.S. air carrier and was paired by airline to ensure crew coordination and cohesion with regard to terminal and surface operational procedures. The flight crews were provided with a forty-five minute briefing to explain the display concepts and evaluation tasks. After the briefing, a 1-hour training session was conducted to familiarize the flight crews with the simulator, the simulated airport, published arrivals and departures, display concepts, and evaluation tasks. The flight crews were asked to maintain good crew resource management and comply with company-specific standard operating procedures.

Simulation Facility

This research was conducted in the Research Flight Deck (RFD) simulator at NASA Langley Research Center (Figure 1). The simulated aircraft dynamics model was a medium- to long-haul commercial passenger aircraft. The RFD configuration is a fixed-based, dual-pilot simulator with a collimated 200° panoramic out-the-window scene. Operations were conducted at the Chicago O’Hare airport (KORD). The out-the-window scene included realistic taxiways and runways with appropriate markings, airport lighting, and other

aircraft in various simulated weather/lighting conditions. The visual acuity of the out-the-window scene was 20/40 (pixels per degree). The RFD was equipped with a 30 ° Horizontal x 24 ° Vertical Head-Up Display (HUD) located on the left or captain's side.

As shown in Figure 1, the simulator has four large main instrument panel displays referred to as: (left to right) Pilot's Primary Flight Display (PFD), Pilot's Navigation Display (ND), Co-pilot's ND, and Co-pilot's PFD. The four display panels are 17" Liquid Crystal Displays with 13.25" x 10.5" viewable space at 1280x1024 (SXGA) resolution and a 5:4 aspect ratio. The RFD includes a Mode Control Panel (MCP), Flight Management System (FMS), Control Display Units (CDU), and hydraulic side-stick control inceptors (Figure 1).



Figure 1 - Research Flight Deck Simulator

Two Electronic Flight Bags (EFBs) were installed, one for each pilot. The EFBs are mounted above and outboard of the side-stick control inceptors near the side window sill. The EFBs utilize a dynamic menu interface using the line select buttons or touch-screen operation. Custom software was developed to provide desired experimental functionality, including CPDLC, airport maps and charts. The airport map page and charts pages displayed standard FAA diagrams that enabled the pilots to zoom and pan utilizing available buttons on the interface.

Display Formats

Flight deck display concepts were developed to evaluate how data-link may be implemented for NextGen and how best to optimally display that information to the flight-crew. In the following,

candidate flight deck display concepts are shown. These concepts have been designed, based on current state-of-the-art flight deck display concepts (Boeing 787, Airbus A350, & Gulfstream G550) and modified for the study to support terminal area and surface operations. These candidate solutions were evaluated against the envisioned NextGen issues and instantiations of data-link.



Figure 2 - Primary Flight Display

Primary Flight Display

The PFD, ND, and Engine Indication and Crew Alerting System display (EICAS) were modeled after Boeing 787, Gulfstream G550 and Airbus A350 instrument panels as current state-of-the-art production aircraft. The PFD display unit includes an ATC message area (CPDLC message area; Figure 2) on the outboard third of the display unit showing incoming and outgoing ATC data-link communications in alpha-numerical format. Incoming messages are color-coded green while outgoing messages are white. All messages are time-stamped. The captain's inboard display unit shows navigation and EICAS displays.

Navigation Display

The first officer's inboard display is a full-screen moving map ND with high airport surface detail. Unlike today's equipage, surface and airborne traffic icons were included to simulate an ADS-B-In (Automatic Dependent Surveillance Broadcast) environment. This display automatically transitions to the surface map display (described below) after landing, when the ground speed is less than 80 kts (Figure 3).



Figure 3 - Navigation Display

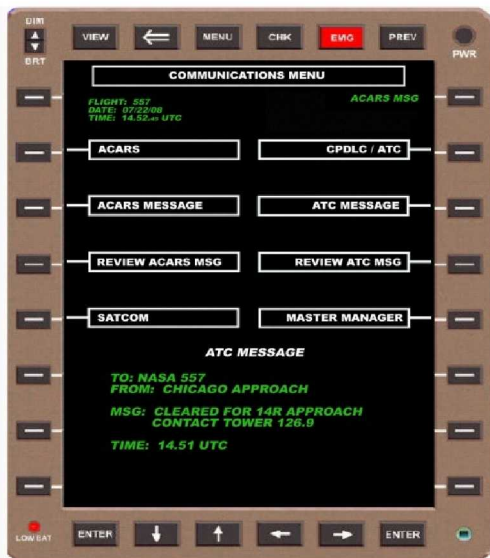


Figure 4 - Electronic Flight Bag

Electronic Flight Bag Display

The EFB, shown in Figure 4, is used as the flight crew's interface for ATC data-link communications, approach chart and airport diagram chart references. The CPDLC/ATC functionality was modeled from existing commercial aircraft vendor interfaces.

Head-Up Display

The HUD surface operations concepts, Figure 5, evolved from Taxiway Navigation and Situation Awareness ("T-NASA") research [18] and Runway Incursion Prevention System research [19]. The HUD showed current ground speed in digital format, the current taxiway, next cleared taxiway,

and centerline markers for the cleared route (CPDLC-assigned route).

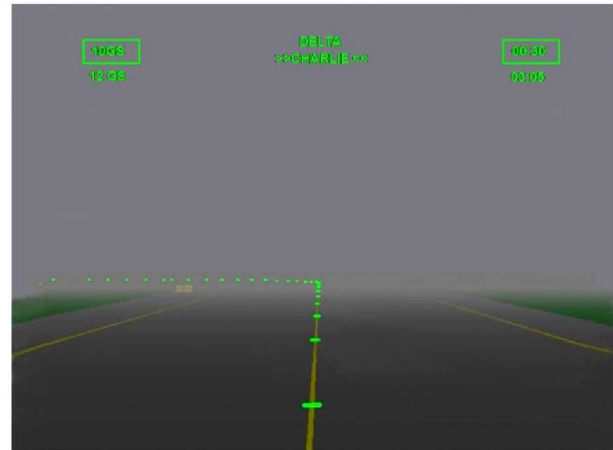


Figure 5 - Heads-Up-Display Concept

In addition, the HUD format included modifications to accommodate emerging NextGen 4DT surface operations. Speed- or time-based taxi guidance was calculated and explicitly shown on the HUD. The 4DT speed and time symbology guided the flight crews throughout the taxi route to regulate and meet the required precision of 4DT surface operation.

Surface Map Display

The nominal surface map display, Figure 6, is an enhanced version of the track-up navigation display. Own-ship position is indicated by the large white chevron. The surface map is automatically displayed on the ND during the landing rollout or it can also be manually selected at any time.

The surface map display enhancements were experimentally added as part of the studies. These enhancements may help to enable 4DT compliance and situation awareness. The surface map display designs largely reflect current RTCA SC-183 working group findings in regard to element shape and color assignments, and is designed for strategic use for surface operations (to minimize head-down time). For instance, when surface traffic is included, medium tan colored chevrons are shown on the display when on the surface and cyan when airborne. When the cleared taxi route is graphically shown, it is drawn in magenta for own-ship.

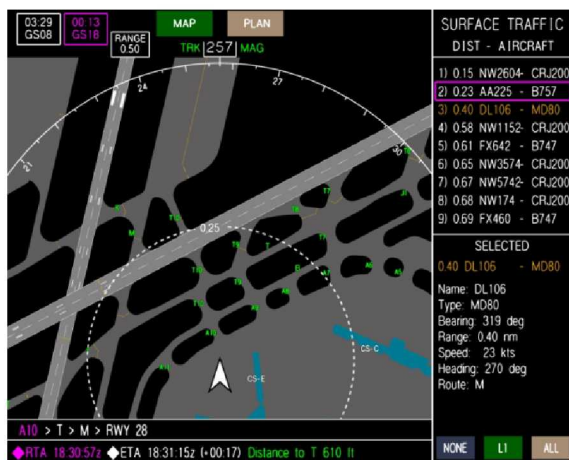


Figure 6 - Surface Map Display

Additionally, the alphanumeric display of 4DT guidance and traffic status/intent data was added to aid in 4DT surface operations. For instance, one enhancement was a list of aircraft position and associated state data (obtained from a modeled ADS-B, TIS-B, and CPDLC-all surveillance source). This traffic list is shown on the right side of the display, sorted by proximity to own-ship with the closest traffic listed first. A cursor control device can be used to select specific traffic in the list (magenta box indicates selected traffic) which brings up additional details of the selected traffic (lower right of Figure 6). Traffic details included: type, flight ID, speed, heading, ATC assigned route (intent), and the range / bearing from own-ship position. Own-ship-assigned taxi route could be displayed on the lower center of the display as a text string, and current position along that route is highlighted in magenta text. Distance to the next route segment is also displayed nearby in green text. 4D trajectory guidance information (textual) could also be displayed textually on the bottom of the ND: current state information in white [ground speed, elapsed time, and Estimated Time-of-Arrival (ETA) UTC]; while guidance information [Required Time of Arrival (RTA) in Greenwich Mean time (UTC), Required Time En-route (RTE) in min:sec] was shown in magenta. Actual ground speed in white and guidance ground speed to meet RTAs was displayed textually in magenta in the upper left hand corner of the ND.

For the advanced traffic intent surface map display concepts, when selected by the flight crew, a traffic's chevron was highlighted with a white

halo and the intended (ATC assigned) route was graphically depicted on the map in the traffic icon color (see Figure 7). This graphical routing information was augmented with a visual depiction of 4DT guidance. A guidance cue - a magenta dot - was shown on the commanded route, moving along the ATC-assigned route approximately 30 seconds ahead - and an own-ship speed symbol - a white circle - showing own-ship position estimated in 30 seconds from present speed and acceleration. The flight-crew's task was to overlay the 30 second speed trend symbol (circle) over the 30 sec RTA prediction symbology (dot). The same indications of traffic intent were shown for selected traffic. The symbology is designed such that conflict areas (such as crossing routes) can be quickly seen and interpreted at a glance. Further, the 30 second ahead gives strategic planning information which could aid in possible traffic conflicts. End-of-route symbology was also shown using a white and magenta diamond to indicate relative ETA and RTA graphically.



Figure 7 - Advanced Surface Map Display

Experiment One Conditions

Experiment One was designed to evaluate how data-link implementations and mixed-modality communication (i.e., voice and data-link) impact crew decision-making, workload, situation awareness, and crew coordination for possible NextGen (circa 2008 through 2025) operational situations. To reflect evolutionary applications of data-link and CPDLC, the research examined four communication modes that have been identified to represent the gamut of potential technological implementations:

- **Data-Link + Voice:** The voice + data-link condition (where data-link is redundant to voice) required the pilot-not-flying to respond via both voice and data-link to ATC clearances. All ATC clearances were provided by both voice and CPDLC and heard on the VHF (“party-line”) broadcast. This condition retains the benefits of voice and adds the capability for retention and review of the message in the cockpit. However, this method may significantly increase the workload of ATC and the flight crew and does not reduce the VHF bandwidth.

- **Data-Link + Read-back Only:** The voice + data-link condition (where data-link is supplemental to voice) stipulated that pilots provide radio read-backs on the VHF channel of received data-link messages. ATC sent all clearances via data-link messaging and all flight crews were required to respond by voice (a condition in which CPDLC was supplemental to voice). This condition reduced the VHF chatter by 50% (except for ATC non-routine communications) and retains the retention/review of the message in the cockpit. This method also retains the “read-back” as a checking mechanism as to whether the communication was correctly received and understood. The advantage of this method is that the communication frequency is reduced but possibly not sufficiently, and ATC must use both voice (listening) and data-link concurrently.

- **Data-Link Only:** The “data-link only” condition (i.e., data-link as replacement for voice or voice-by-exception) had no ATC clearances or pilot read-backs over the voice channel and the participants were required to respond only through data-link (except for exigent situations or non-routine communications). This technique provides the maximum VHF bandwidth reduction and simplifies the communication to a single modality. However, this condition also represents the loss of the auditory communication benefits (party-line, intonation, stress, etc.)

- **Data-Link + Intent:** The data-link only + traffic intent condition was identical to the data-link only condition (i.e., data-link as replacement for voice) but presented additional traffic intent information (e.g., selected traffic route and destination information). The condition was introduced to determine whether providing traffic

intent to the flight crew, shown on the surface map display (see Figure 8), may mitigate safety issues described by other research studies as a consequence of reduced voice communications and loss of party line information.

Experiment Two Conditions

For this experiment, intent is operationally defined as the information that collectively provides own-ship and other aircraft state and assigned 4DT route guidance and prediction (e.g., ADS-B in/out surface message; CPDLC-all; TIS-B; etc). The objectives of Experiment Two were to determine what critical elements are needed to enable EVO and 4DT surface operations efficiently but above all, safely. Essentially, the questions being asked are: whether it is sufficient to just present the traffic intent information textually (e.g., data-link clearances of other aircraft); or, 2) is it required to have a graphical interface of traffic intent display.



Figure 8 – Own-ship Route & Traffic

For this experiment, the display conditions were:

- A baseline NextGen aircraft capability to include a surface map display with own-ship only and CPDLC capability with textual traffic state information (see Figure 6);
- An intermediate NextGen concept to include a surface map display with traffic and manual query capability of other aircraft intent and graphical depiction of own-ship, target aircraft, and 4DT paths (see Figure 8);

- An advanced NextGen concept that automatically prioritizes and selects aircraft while depicting graphical own-ship and traffic 4DT guidance and conformance (see Figure 7).

Experimental Design

The results presented herein were part of a larger research study consisting of three experiments that were conducted over two-days of testing for each flight crew. The experiments ran sequentially and the first two experiments are described here. The experimental design was a mixed-subjects factorial design. The independent variables of interest were communication mode (Experiment One) or surface map display concept (Experiment Two) for nominal (within-subjects) and off-nominal trials (between-subjects). All flight crews experienced each of the four off-nominal trials but the communication mode (4 levels) or display concept (3 levels) for each trial was randomly varied across the participants. Therefore, each flight crew saw all four off-nominal events but with each of the different communication modes or display concept such that across all flight crews there was a balanced presentation of off-nominal events paired with communication mode or display concept dependent upon experiment.

All 20 nominal trials were presented in the same order to the flight crews but was randomly ordered in which communication mode was paired with that trial. The nominal trials provided the flight crews with experience with the various communication modes and the varying geometries of terminal maneuvering area procedures available at KORD. The nominal trials also served to increase the total number of trials to provide the necessary experimental matrix to introduce the off-nominal trials and to best replicate the operational conditions most likely to produce errors.

The dependent variables included quantitative and qualitative measures. The quantitative measures included 4DT adherence and conformance (e.g., commanded and actual speed delta), flight technical error (e.g., root-mean-squared-error of aircraft position from taxi centerline), pilot control inputs (e.g., toe brake force, control wheel column and tiller inputs), off-nominal detection and response, and flight crew communication acts [21]. The qualitative measures

included Likert-type post-run questionnaires, Situation Awareness Rating Technique, and NASA Task Load Index, and post-experiment paired comparisons for Situation Awareness (SA) – Subjective Workload Dominance (SWORD).

Rare Event Scenarios

An overview of the off-nominal rare event scenarios are presented in the following.

Erroneous Data-link Clearance. The first off-nominal scenario was created by an incorrect data-linked clearance that produced a route disconnect. The erroneous data-link inclusion would result in the aircraft turning back toward the active runway instead of toward the concourse creating a potential runway incursion situation.

The data link clearance was in dissociation with the voice clearance (for those conditions that had voice) in that the clearance was stated correctly by the controller over the voice channel. Therefore, the flight crew could detect the anomaly if they heard and understood the dissociation between the voice and data-link clearances or by reviewing the data-link clearance fully prior to acknowledging comply with WILCO (or later during taxiing). It was hypothesized that voice (as redundant to data-link) would result in greater awareness and likelihood of detection of the error because the flight crew would have more opportunities to realize the error.

Data-Link Clearance Received for Other Aircraft. The second off-nominal scenario examined the effect of erroneously receiving a data-link clearance intended for another aircraft. The scenario began with an approach to Runway 22R. The proper data-link clearance was received prior to the final approach fix containing the correct landing and taxi routing data. Approximately 0.5 nm from the runway threshold, the aircraft received a second landing clearance that was erroneously sent to the aircraft although it was intended for another aircraft conducting operations on a proximate runway. The clearance contained a similar taxi clearance as the previous CPDLC message but also had errors that would result in a route dissociation between the landing runway and the taxi instructions.

The erroneous message was hypothesized to be generated by a controller error where the message

was sent to and contained a transposed aircraft call sign (which was similar to the own-ship aircraft). For those conditions that included voice, the voice clearance was accurate and correctly stated the intended aircraft call sign and taxi clearance. The hypothesis was that, during the high workload phase of the approach when the incorrect clearance was received, the flight crew would not be able to attend to the CPDLC message and would accept the clearance without review. This contrasts with the flight crews who also heard the voice clearance, thus, providing them an additional opportunity to recognize that the taxi clearance was not congruent with the landing runway and was not intended for their aircraft.

Taxiway Conflict. The third off-nominal scenario evaluated whether the flight crew would be task-captured by the 4DT task. The scenario began as a taxi-out task in which the aircraft received push back and taxi clearance to the departure runway with RTA instructions. Once the aircraft accepted the clearance, another aircraft subsequently landed and turned off with a taxi clearance to Delta. The conflicting aircraft communicated on tower frequency, that they were unsure where Taxiway Delta was. The conflict aircraft mistakenly turned on the Taxiway Mike instead of the second taxiway (Delta) resulting in a potential nose-to-nose situation.

The objective of the scenario was to determine if any of the experimental conditions would result in significant head-down time and increased intra-cockpit communications that may prevent the timely identification of the other traffic. (The scenario was not intended to result in a collision but would have resulted in a nose-to-nose situation requiring ground vehicles to tow the aircraft if not detected in an adequate amount of time.) The hypothesis was that the flight crew that had either of the voice and data-link conditions would more easily recognize the potential conflict and would be proactive in avoiding the situation because of the reduction in hypothesized intra-cockpit communication and reduced head-down time. The flight crews that had only data-link (e.g., data-link only and data-link + intent) would instead be reactive in detecting the situation because of increased communication and head-down time

involved in interacting with the EFB and surface map displays.

Approach Runway Incursion. The final off-nominal scenario for Experiment One (data communication) created a potential runway incursion in which an aircraft erroneously taxied onto the runway and held despite it being cleared for take-off while the subjects were on final approach to the same runway. The blundering aircraft had responded to ATC, but did not correctly acknowledge the clearance, and the controller failed to recognize the error (expectancy heuristic). The aircraft consequently remained on the runway, unaware that they were supposed to depart because of the aircraft on approach behind them.

It was hypothesized that having party-line information would cue the flight crew that an aircraft was holding on the landing runway. Also, having data-link with traffic intent might also alert the flight crew to the runway hazard.

ADS-B Surveillance Failure. An off-nominal scenario for Experiment Two, examining the display and use of traffic intent data received by aircraft, evaluated pilot behavioral response to a surveillance source failure. Own-ship was taxiing in low-visibility conditions (1200 RVR). However, traffic was displayed on the surface map (either textually and/or graphical icons) and in the FLIR on the HUD. After turn-off from the active runway, the aircraft taxiing in front of own-ship lost the capability to broadcast their intent or positional information. At this time, the aircraft was removed from the traffic list and, if available, the traffic icon representing that aircraft disappeared from the surface map display. The scenario was designed to test whether the flight-crew would notice the absence of critical information in the surface map display.

Taxi Aircraft Blunder. The next off-nominal scenario for Experiment Two involved a runway incursion scenario. Another aircraft taxied into position for an intersection departure when ATC had already cleared own-ship for departure. This scenario evaluated if and how the flight crew were alerted to this unsafe condition, either by: (a) ATC-pilot voice communication (present in all Experiment Two scenarios); (b) detecting the aircraft on the surface map; or (c) seeing the aircraft in the HUD FLIR during take-off roll.

Non-Participating Vehicle on Surface. A significant concern for current and future surface operations is the prevalence of vehicular traffic that is non-participating in communication, navigation, or surveillance in the airport movement area. This scenario was designed to test whether the flight crews would get complacent and rely on the surface map display of traffic information and not adequately scan for other traffic and vehicles. The flight crews were aware of the presence of significant vehicle traffic, representing typical KORD operations, and that these vehicles were not under positive surveillance by ATC or position broadcast to own-ship. During this scenario, a fire-truck was taxiing on the ramp area but got lost and notified ATC that they may be on a taxiway. The fire truck was in the grass island between two taxiways; however, the wingspan of the 757 would clip the top of the fire truck. Because the fire truck was broadcasting its position, it was not iconically shown on surface map but was visible with FLIR and OTW. The scenario was designed to test whether the HUD near-domain information (e.g., symbology) would task capture the pilot taxiing and/or whether the surface map displays would induce reductions in OTW scanning.

Controller Mistake Clearing Own-ship Across Active Runway. The final off-nominal scenario tested in Experiment Two involved a similar scenario as the taxi aircraft blunder except that own-ship was set-up to cause the incursion. In this scenario, own-ship was cleared to cross the active runway at which time another aircraft was cleared into position-and-hold for take-off. As own-ship was approaching the hold short line, the tower cleared the other aircraft for take-off. This scenario evaluated if and how the flight crew were alerted to this unsafe condition, either by: (a) ATC-pilot voice communication (present in all Experiment Two scenarios) or (b) detecting the aircraft on the surface map.

Experimental Procedure

The flight crews were recruited from a NASA-established protocol. Each crew was given detailed pilot briefing materials prior to their arrival. All flight crews completed an informed consent and were provided a detailed briefing by the researchers upon their arrival. Participants were made aware of the experimental variables under test but were not

cognizant that off-nominal events would be presented (this was confirmed in post-experimental debriefings). Three briefings in-total were presented over the two days of testing with each briefing focusing on the specific research objectives. A 90-minute training session was conducted prior to the start of each experimental phase, and pilots were trained to an asymptotic or equivalent level of performance based on researcher observations and pilot feedback.

Experiment One: Data Communication

After training, twenty-four trials (20 nominal trials and 4 off-nominal trials) were conducted with the appropriate breaks included for each day of testing (i.e., data communication and traffic intent experiments). Prior to each trial, the pilots were briefed on the evaluation task (e.g., approach to Runway 10) and were provided time to configure the aircraft for the operation (i.e., approach, departure, or taxi) and brief the procedure. Once the flight crew indicated they were ready, the trial began including a data-linked CPDLC message that was announced with a chime and displayed on the PFD CPDLC window and the EFB communication sub-menu. The First Officer (FO) reviewed and acknowledged the message through the EFB (through a quick key access on main menu). Dependent upon the evaluation task, the trials lasted between 5 and 10 minutes. Pilots were asked to adhere to the speed and time commanded guidance to meet the RTA within a defined tolerance (± 5 kts and ± 30 sec), but to note any anomalies and to ensure safety of the aircraft at all times. After the trial ended, each pilot was asked to fill out several questionnaires that were administered on selected runs (12 experimental runs) that represented a cross-section of the nominal runs or were nominal analogs of the off-nominal trials.

Experiment Two: Traffic Intent. The experimental procedures for Experiment Two, which evaluated various surface map and traffic intent display concepts, were identical to Experiment One. The notable exception was the four different off-nominal events that were inserted in the experimental matrix. These off-nominal events were fundamentally different than the off-nominal events in Experiment One and pilot debriefing confirmed that they were undetected. Full data-link and voice communications (data-link +

voice) were used in the experiment to avoid confounds and to provide a consistent set of environmental conditions across flight-crews and display conditions.

Experiment One Results

The experiment, as a whole, had numerous objectives. The focus here is on the off-nominal results and qualitative data that reflect the efficacy of communications and display conditions to detect and recognize errors with flight-deck data-link CPDLC communications and off-nominal event detection with the various surface map display concepts. Quantitative data was collected for the nominal trials and is presented elsewhere [20].

All significant results are presented using an *a priori* significance (α) level of 0.05. Analyses of Variances (ANOVAs) were performed when appropriate Multivariate Analysis of Variance (MANOVA) tests were found to be significant. No significant results were found between Captain and FO qualitative ratings ($p > 0.05$) and, therefore, are grouped for analyses.

4DT Conformance and Taxi Performance

An ANOVA found no significant main effects across the four communication modes for cross-track root-mean-squared error, $F(3,94) = 0.867$; ground speed deviation from commanded 4DT ground speed, $F(3,94) = 0.748$; and time deviation from RTA for the nominal analog or equivalently designed trials, $F(3,94) = 1.180$. Generally, the flight crews ranged from 16.45 to 27.45 Root Mean Square (RMS) error and maintained speeds within 1.5 knots of commanded groundspeed allowing the aircraft to conform to RTA times within 2.5 seconds of assigned RTA. Therefore, these results demonstrate that flight-crews are able to maintain ground speed commands and adhere to required-time-of-arrival clearances.

Situation Awareness

Situation Awareness Rating Technique (SART). The SART uses the constructs of: 1) demand on attentional resources; 2) supply of attentional resources; and, 3) understanding. Mean values for SART were computed, where the SART rating is “understanding” reduced by the difference

of “demand” minus “supply” (i.e., $SART = [\text{understanding} - (\text{demand} - \text{supply})]$).

ANOVAs on the mean SART ratings found significant main effects across the four communication modes for all four off-nominal events.

- For the “erroneous data-link clearance” event, there was a significant effect found, $F(3,24) = 5.529$. A Student-Newman-Keuls (SNK) post-hoc test showed that pilots rated the data-link + voice and data-link + read-back conditions to be significantly higher for situation awareness than the data-link only and data-link only + intent conditions.
- The same significant differences in SART ratings by condition was found for the “approach runway incursion” event, $F(3,24) = 7.682$.
- However, SNK post-hoc tests on the significant main effects for both the “taxiway conflict” ($F(3,24) = 13.496$), and “data-link clearance received for other aircraft” ($F(3,24) = 7.362$) events, evinced that the data-link + read-back condition was rated significantly higher for situation awareness compared to the other three experimental conditions.
- In comparison, the subjective SA data for the corresponding nominal trials showed a significant main effect for SART, $F(3,95) = 40.675$. A SNK post-hoc test revealed three subsets: (a) data-link-only (1.54), (b) data-link + intent (3.46) and data-link + voice (3.92) and (c) data-link + read-back (10.25). Therefore, pilots rated the read-back only condition to be significantly higher for situation awareness than the three other conditions and the data-link only to be the worse concept for situation awareness during the nominal trials.

Situation Awareness - Workload Dominance (SA-SWORD) Scale. An ANOVA revealed a significant main effect for communication mode for SA-SWORD, $F(3, 69) = 40.601$. Post-hoc test showed that pilots rated the data-link + read-back condition to be significantly higher for situation awareness than the other three conditions.

Mental Workload

NASA Task-Load-Index (NASA-TLX). The post-run work was assessed using the NASA TLX scale, which is comprised of 6 validated sub-scales that are thought to represent the underlying construct (rated 0 - 100). An ANOVA found no significant main effect for NASA-TLX for any of the four off-nominal trials, $p > 0.05$. The four communication modes were found to be equal in perceived mental workload as rated by the NASA-TLX scale. However, for the nominal trials, there was a significant main effect for NASA-TLX, $F(3,95) = 11.719$. SNK post-hoc tests revealed three subsets where the pilots rated the data-link + read-back condition (23.58) to be significantly lower for workload than the other three display conditions. The data-link + intent (35.32) and data-link + voice (43.31) were both rated significantly lower than data-link (54.07).

Subjective Workload Dominance (SWORD) Scale. An ANOVA revealed a significant main effect for communication mode for SWORD, $F(3,69) = 68.169$. Post-hoc comparisons evinced that pilots rated the data-link + voice (data-link as redundant to voice) significantly higher in mental workload on the SWORD post-experiment paired-comparison scale compared to the other three conditions which did not differ statistically from each other ($p > 0.05$).

Communication Awareness

Questionnaire Responses. Significant main effects were found for communication mode for post-run questionnaire item for communication awareness for the off-nominal events of “taxiway conflict”, $F(3,24) = 7.527$, and “approach runway incursion”, $F(3,24) = 8.842$. SNK post-hoc tests revealed that the data-link + read-back condition was rated significantly higher for communication awareness than the other display conditions which did not differ for this measure.

Analyses for qualitative reports of communication awareness taken during the nominal trials also revealed a significant communication mode main effect, $F(3,95) = 44.49$. SNK post-hoc test showed three subsets: (a) data-link only was rated lowest for awareness of aircraft clearances and party-line information, (b) data-link + intent and data-link + voice was rated higher than data-

link only but poorer for communication awareness compared to data-link + read-back, and (c) data-link + read-back was qualitatively rated the highest for the construct than the other three communication modes.

Post-Experimental Paired Comparison. An ANOVA revealed a significant main effect for communication mode for communication efficacy, $F(3,69) = 29.635$. Post-hoc Least Significant Difference (LSD) comparisons showed that pilots rated the data-link + voice and data-link only conditions to be significantly lower for communication effectiveness than both the data-link + Intent and data-link + read-back only conditions. There were no significant differences between the data-link + Intent and data-link + read-back only conditions.

Off-Nominal Event Detection

Erroneous Data-link Clearance. There were 3 off-nominal events per experiment condition across the 12 flight crews. Ten of the flight crews correctly recognized the erroneous data-link clearance (the inclusion of “Mike Four” in the taxi clearance) and contacted ATC to query the clearance and/or reject the clearance. The two instances where the erroneous clearance was not detected occurred for the data-link only condition.

Data-Link Clearance Received for Other Aircraft. All the flight crews with either the data-link only or data-link + intent condition failed to detect the data-link clearance received intended for another aircraft and accepted the new clearance despite being within 1 nm on final. Upon taxi, these flight crews realized that the taxi instructions resulted in a route disconnect from the active runway to the ramp area and contacted ATC to request new taxi instructions. However, none of the six flight crews with data-link + voice or data-link + read-back accepted the data-link clearance and correctly recognized that the data-link message was not specific to their aircraft. These flight crews ignored the CDPLC message and contacted ATC to query the message after turn-off.

Taxiway Conflict. The data showed that none of the flight crews – irrespective of the experimental condition - experienced a taxiway conflict. Because all the conditions had a HUD with a forward-looking-infrared (FLIR) enhanced

vision system, the Captain was able to detect the traffic taxiing toward them on the same taxiway. The results showed the significant advantage that an enhanced vision system provides for low-visibility operations, especially in this scenario.

Approach Runway Incursion. For the data-link only condition, there was one runway incursion (33% of the flight crews) that occurred because the flight crew was entirely unaware that an aircraft was in position-and-hold awaiting take-off clearance when the aircraft landed on the active runway. For the data-link + intent condition, the flight crews were able to adequately recognize and avoid the incursion but were slow in identifying the evolving situation and reported significant workload in interfacing with the traffic intent data and determining what the aircraft was intending to do. In contrast, the flight crews in both the voice conditions began discussing the aircraft on the active runway upon hearing the clearance and then recognizing that the incursion aircraft had not taken-off and had ample time to discuss options, initiate a go-around, and contact ATC as to their situation.

Experiment Two Results

Detailed data analyses for Experiment Two are still ongoing and are not available in time for publication herein. The off-nominal event detection results are discussed in the following.

Off-Nominal Event Detection

ADS-B surveillance failure. There was a significant difference across the three display conditions in terms of detection and recognition of an ADS-B surveillance failure.

All flight crews detected the ADS-B failure in the own-ship route and surface traffic with intent display condition. In all cases, the first officer noticed the absence during selection of aircraft on the surface map. Pilot de-brief reports suggest that these pilots were actively using the surface map display concept because of the presence of valuable and useful graphical traffic intent information. The loss of surveillance data in this case was obvious.

One of four flight-crews failed to detect the missing aircraft, despite the presence of traffic icons in the own-ship route and surface traffic display. Often the Captain noticed the aircraft in the HUD

FLIR and would remark on the absence of the aircraft on the surface map. In one case, neither pilot noticed the anomaly.

Three of the four flight-crews with the own-ship only surface map displays did not detect the ADS-B failure. The reason was due mostly to the lack of traffic icons on the surface map.

In the later two cases, the use of textual display of traffic intent data required significant cognitive overhead to select and interpret information and required a manual selection process to get traffic state and intent data. The crews consequently did not often use this capability to its fullest extent. This reduces the amount of time spent evaluating the surface map display and noting changes and discrepancies in the data presented.

Taxi aircraft blunder. In this off-nominal scenario involving a runway incursion during own-ship departure, only one of the twelve flight-crews failed to notice the blunder. The data suggests that this is largely owing to the use of the FLIR to detect the aircraft. The flight-crews reported significant value from the HUD FLIR in preventing this conflict and also, the supplemental utility of hearing voice communications in which they were made aware that an aircraft was holding short down the runway. Additionally, the depiction of traffic on the surface map was observed to significantly enhance situation awareness although it was primarily used to confirm the detection of the traffic in the HUD FLIR.

Non-participating vehicle on surface. This off-nominal scenario tested whether flight-crews would fail to notice a vehicle which was not visible on the surface map. The scenario was made more challenging because the fire truck had stopped just beyond a taxiway intersection. The HUD field-of-view would not provide much detection.

All flight crews were able to detect the fire truck suggesting that the presence of a surface map display head-down or the near-domain information presented on the HUD did not distract the crew from the task of scanning OTW for obstacles and traffic. All the flight-crews detected the vehicle OTW with the exception of two flight-crews who noticed the fire truck in the HUD FLIR during taxi out of the ramp area.

Controller mistake clearing own-ship across active runway. In this scenario, own-ship was cleared to cross the active runway but, after several ATC communications, ATC also cleared another aircraft to take-off. All flight-crews were able to detect the potential incursion situation and stop the aircraft.

Two of the four flight-crews, using the own-ship only display, were not able to stop short of the hold-line. This is technically a runway incursion. All flight-crews with the other two display conditions were able to stop short of the hold-line.

The majority of these flight-crews detected the potential conflict from the party-line radio broadcast of the erroneous clearance for the other aircraft to take-off. They were also able to verify this situation by evaluating the surface map display if it included traffic. The lack of surface traffic reduced the lead-time available to the flight crew to mitigate the potential runway incursion.

In this scenario, the HUD and its enhanced vision capability was not useful because the incursion aircraft was significantly outside the field-of-view of the HUD.

Conclusions

The research objective was to evaluate the flight deck impacts of different data-link implementations that may be considered as options for ATC-pilot communications for NextGen.

Across all off-nominal conditions, the results demonstrated that data-link only is not an optimal solution for these operations and corroborates previous research which advises caution for a voice-by-exception system because of the significant concerns for reduction of party-line and situation awareness on the part of the flight crew. The voice-by-exception experimental condition was almost universally the highest workload and lowest situation awareness condition. The off-nominal results confirmed the finding that voice for routine communications significantly enhances situation awareness for terminal maneuvering area operations.

The subjective and off-nominal data showed that the data-link + read-back condition was clearly the best option across almost all the dependent variables tested. By requiring pilot read-back of CPDLC, flight crews responded that they were able

to retain the party-line broadcast awareness because they knew what the other traffic was “intending” to do while at the same time reducing the voice congestion based on the specified traffic density and scripted clearances and pilot responses used in present study. This also significantly freed up the frequency to allow the flight crews to more easily contact the controller if necessary (e.g., non-routine communications).

The off-nominal detection results from Experiment Two further supplements the finding of Experiment One. The results posit that a surface map display with traffic significantly enhances situation awareness and would be a significant complement to a data-link + read-back only approach to data communication and CPDLC. For 4DT operations, the use of graphical depictions of 4DT RTA guidance and conformance compliance seems to further enhance flight-crew capability although data analyses to date make any conclusions premature.

Overall, the results demonstrate the substantial importance of providing some party-line capability for any new ATC-pilot data communication system. The conclusion drawn here is that a promising solution may be the use of mandatory pilot read-back of CPDLC data-link routine clearances in the terminal maneuvering area, particularly with a surface map with traffic display, and the use of voice communication for all non-routine and exigent communications; however, the effect of such an approach on the controller has yet to be evaluated and the experiment did not specifically evaluate controller-pilot interactions. The conclusion matches that observed during the CASCADE D-Taxi trials at Brussels [22] which recommended the use of mandatory pilot read-back as, “...effective mitigation means against erroneous or non-intended clearance details in the sent message” (p. 83) and that a flight-deck display of ground traffic would significantly enhance situation awareness for data communications in the airport movement area.

Future Directions

Although the issues of “data-link only” have been well-documented in the literature for aircraft operations typical of today’s system, this “voice-by-exception” data-link protocol continues

to remain the primary communications end-state. The conclusions drawn from the results presented herein mirror other research and share the concerns for implementation of a safe and effective “data-link only” system for the terminal maneuvering area. Although voice-by-exception permits voice communication - and requires voice for non-routine communications - research suggests that there are ample situations and opportunities in which a data-link only approach may reduce safety margins. The use of mandatory pilot read-back of CPDLC data-link routine clearances in the terminal maneuvering area appears promising and will be explored further.

This research has also demonstrated the utility of flight-deck displays of traffic information for surface operations for enhancing situation awareness and safety and mitigation of human error. This work will continue to evaluate methodologies and define whether the visual display of traffic intent and other information might



possibly provide mitigation for the safety concerns within a voice-by-exception environment.

Figure 9 - Runway Incursion Alerting During Approach

Finally, the present results demonstrate that flight crews were able to adhere to required-time-of-arrival clearances without significant effort even under reduced visibility conditions and NextGen-like traffic densities. Results from the traffic intent research showed that graphical presentation of own-ship and other traffic intent significantly enhanced situation awareness and conflict detection; however, full data analyses are not completed at time of

publication. Future research will focus on optimization of 4DT algorithms, advanced display technologies, and conflict detection and alerting (Figures 9-10) to meet these and other challenges to NextGen operations.

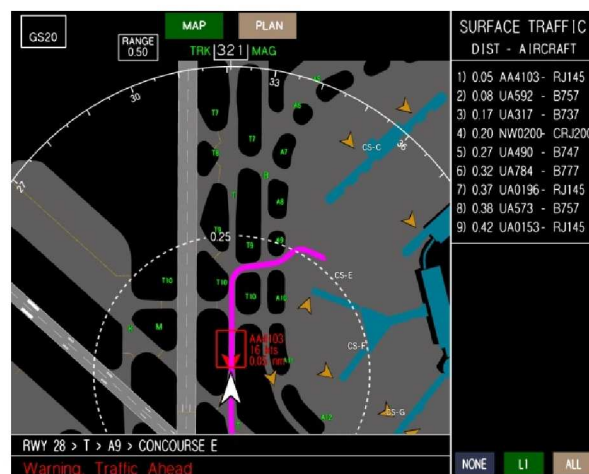


Figure 10 – Taxi Conflict Alerting

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