

DIGITAL TAXI CLEARANCES IN AIRPORT TRAFFIC CONTROL TOWERS – INTERFACE DESIGN AND RESULTS FROM A HIGH-FIDELITY SIMULATION EXPERIMENT

Todd R. Truitt, Ph.D.
Federal Aviation Administration
Atlantic City International Airport, New Jersey 08405

The experiment examined the effects of Digital taxi (D-Taxi) clearances when either 40% or 75% of the departure aircraft were data link equipped and compared these conditions to voice-only operations. Sixteen Airport Traffic Control Tower controllers used the Tower Operations Digital Data System at the ground control and local control positions to control airport traffic with a 270-degree simulated out-the-window view. The controllers worked at each position in each experimental condition, provided ratings of subjective workload, and responded to questionnaires. D-Taxi clearances for departure aircraft reduced voice communication between pilots and the ground controller when 75% of the aircraft were data link equipped, without increasing workload or heads-down time. On average, the controllers took 1.28 s to construct and issue a D-Taxi clearance, and they preferred D-Taxi to voice because it reduced their communication duties and removed the potential for readback and hearback errors.

The air traffic controllers in Federal Aviation Administration (FAA) Airport Traffic Control Towers (ATCTs) manage the aircraft moving on the airport surface as well as airborne aircraft that are arriving or departing the airport. The ground controller establishes a sequence for departures and provides taxi clearances to maintain efficient use of the runways and a smooth flow of aircraft to and from the ramp. Currently, ground controllers issue all clearances to pilots via radio voice communications. The FAA has identified Data Communications (Data Comm) as an enabling technology for Next Generation Air Transportation System (NextGen) operations to manage aircraft on the airport surface (Joint Planning Development Office, 2007). In particular, the FAA proposes that ATCT controllers use Data Comm for digital-taxi (D-Taxi) clearances. D-Taxi clearances for taxi-out (i.e., departure) operations may include information such as current Automatic Terminal Information System (ATIS) information or Data Link Operational Terminal Information System (D-OTIS) information, detailed taxi route instructions, and “hold short” instructions. Controllers would not use D-Taxi for time-critical events such as clearances to begin taxi movements, to cross runways, or to transfer control. Fundamental to enabling an effective Data Comm system will be the controllers’ ability to manage these digital messages, using effective display designs and supporting automation capabilities in a mixed equipage environment. ATCT and airport surface operations may benefit as a result of the interaction between Data Comm and automated decision support tools, including (a) increased safety in the National Airspace System by providing tools for conformance monitoring and increasing situation awareness, (b) improved controller productivity by reducing controller and pilot workload, and (c) increased capacity by enabling advanced operations via an effective user interface that will reduce instances of human error. To implement Data Comm, the FAA must conduct concept and operational research to identify the advantages and limitations of data link communications. The Data Comm research will also generate an initial set of system requirements that all stakeholders can use as a foundation for future development. The experiment presented here examined Data Comm concepts for ATCTs using a high fidelity, human-in-the-loop simulation.

Method

Current ATCT controllers worked in a high-fidelity simulator at the FAA Research, Development, and Human Factors Laboratory to compare two levels of aircraft Data Comm equipage and a voice only, baseline condition. The Data Comm capability allowed the controllers to receive digital requests for taxi clearances and issue D-Taxi clearances for outbound aircraft. The experiment used a 2 (Run number – First vs. Second) x 3 (Condition – Voice Only, 40% Data Comm, 75% Data Comm) repeated measures design.

Participants

Sixteen Certified Professional Controller (CPC) ATCT controllers served as participants (14 male, 2 female). They were on average 41.3 yrs ($SD = 8.5$) of age, and had worked as an ATCT controller for an average of 17.0 yrs ($SD = 9.6$). All of the controllers had normal or corrected-to-normal vision.

Apparatus

The ATCT simulator consisted of three controller workstation displays situated within a 270-degree out-the-window (OTW) view that comprised nine, 73" high definition televisions. A standard 20" computer monitor presented Standard Terminal Automation Replacement System (STARS) radar data. Two VarTech Systems, Inc. touchscreen displays enabled the Tower Operations Digital Data System (TODDS). All of the displays rested on one of two height-adjustable tables. We placed a Workload Assessment Keypad (WAK; Stein, 1985) at each controller position and mounted two cameras and two microphones above each controller position. The cameras recorded interactions with the TODDS and the microphones recorded all ambient sound. We mounted a camera in front of the controllers to capture their point of gaze (e.g., TODDS, OTW). Six simulation pilots, each with their own workstation and communications system, communicated with the ground and local control positions.

The TODDS consisted of two touchscreen displays, one for each control position. Each touchscreen had an active display area of 17" (43.2 cm) wide and 12.75" (32.4 cm) high with a 1,600 x 1,200-pixel format, and had a viewing angle of 85 degrees. Each touchscreen had an associated Airport Surface Detection Equipment – Model X (ASDE-X) keyboard and a trackball/keypad as additional input devices. The TODDS presented electronic flight data in the form of Flight Data Elements (FDEs), surface surveillance data – including aircraft position and associated data blocks – weather information, and the ability to construct and issue D-Taxi clearances. This integrated design placed all of the most important information on a single display for each controller position to simplify information presentation and to reduce the controllers' need shift their visual attention among multiple displays. Figure 1 presents screenshots from the TODDS ground and local control positions. For more information about the TODDS, see Truitt (2006, 2008).



Figure 1. The TODDS ground (left) and local (right) control positions including FDEs, surface surveillance data, and weather information.

TODDS D-Taxi graphical user interface. For the current experiment, we built upon the existing TODDS D-Taxi graphical user interface and functionality (Truitt, 2008) by providing controllers with a means to modify the taxi clearance. A data link indicator appeared on the left side of the FDE and in the center of the second line of the

data block for each departure aircraft that was data link equipped. The data link indicators appeared at both the ground and local control positions, but only the ground controller could issue or cancel a D-Taxi clearance. Aircraft that were data link equipped had an upright triangle that was either open grey (unowned) or filled white (owned). Only one controller position could own an aircraft at any given time (see Figure 2).



Figure 2. Data link capability indicators in the data blocks of owned (left) and unowned (right) aircraft.

When a data link equipped aircraft reached a ramp spot and was ready to taxi, the pilot sent a D-Taxi request via data link to the ground controller and the data link indicator changed to a light blue triangle and pointed to the left. When the ground controller noticed the pilot request, he or she selected the aircraft's data block or FDE to activate the D-Taxi button, highlight the flight data of interest (FDE and data block), and open the readout area in the upper corner above the FDE list. The readout area displayed the specific pilot request in addition to the full set of flight data for the selected aircraft. The ground controller could defer the pilot's request by deselecting the aircraft which caused the data link indicator to appear as an upright, light blue, open triangle. Deselecting the aircraft also closed the readout area and deactivated the D-Taxi button (see Figure 3).

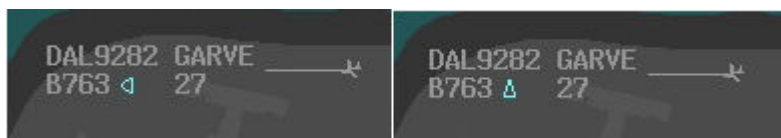


Figure 3. Data link indicator in data blocks for a pilot request (left), and a deferred request (right).

When the ground controller selected the activated D-Taxi button, the TODDS entered the D-Taxi construction mode and an opaque "screen" appeared over the surface surveillance display. The screen dimmed everything except for the aircraft and related elements of interest and prevented the controller from selecting or moving other FDEs or data blocks. In addition to the opaque screen, the TODDS presented a proposed taxi route (indicated by a white line) that included hold short points and a set of D-Taxi construction mode buttons. In the D-Taxi construction mode, the controller could edit the taxi route, add or remove hold short points, send the D-Taxi clearance to the pilot, or cancel the D-Taxi construction and return to the normal mode. To edit the taxi route, the controller placed his or her fingertip on the displayed route and then dragged the route to a different taxiway. Once the controller selected the Send button and transmitted the D-Taxi clearance to the aircraft, the data link indicator in the FDE and data block pointed to the right. Each D-Taxi clearance included the current ATIS information and the taxi route including hold short points. If a data link transmission failed, the data link indicator turned red and the controller could resend the D-Taxi clearance or contact the pilot by voice. If the data link transmission was successful and the pilot accepted the D-Taxi clearance, then the D-Taxi accepted indicator (an unfilled circle) appeared in the aircraft's data block and FDE. If the D-Taxi clearance included a hold short clearance, then the hold short indicator also appeared on the left side of the aircraft's data block (see Figure 4).



Figure 4. Data comm indicators in data blocks for a sent (left), failed (center), and accepted (right) D-Taxi clearance.

The controller then contacted the pilot via voice and instructed the pilot to “resume taxi” to begin the taxi operation. We required the controller to initiate a taxi movement via voice to establish that voice communication was operational and to allow the controller to determine the sequence and timing of departure aircraft. Aircraft with a D-Taxi clearance were subject to taxiway conformance monitoring. The FDE and data block text of a nonconforming aircraft flashed red on both the ground and local control positions until one of the controllers selected the data block or FDE. The data block and FDE continued to display with red text until the aircraft returned to conformance, or until the ground controller canceled the D-Taxi clearance by selecting the D-Taxi cancel button.

Airport traffic scenarios. We used an airport configuration, which was based on Boston, to develop one 40-min base air traffic scenario. Using a 27/33 runway configuration, the scenario had an arrival rate of 36 aircraft/hr and a departure rate of 42 aircraft/hr with arrivals and departures on runways 27, 33L, and 33R. We modified the base scenario by changing the aircraft call signs to create 12 different versions of the same scenario. This reduced the potential effects of traffic demand while preventing the controllers from recognizing identical scenarios. The controllers worked each version of the scenario in a different random order for each group. A scripted data link failure occurred for one aircraft in each scenario.

Procedure

The controllers worked in groups of two. After signing an informed consent statement, they completed a biographical questionnaire, and received training on the airport and procedures. They then completed a touchscreen training protocol and received training on the TODDS before engaging in six practice scenarios (one at each controller position in each experimental condition). The controllers then completed the experimental scenarios where they controlled airport traffic and provided online measures of subjective workload (WAK) every 5 min. The experimental conditions were presented in a counterbalanced order. The controllers completed questionnaires after each scenario and at the end of the experiment.

Results

Airport System Operations

There was a significant effect of Condition on the duration that aircraft waited on the ramp, $F(2, 30) = 9.81, p < .001$. Aircraft waited on the ramp longer in the 40% Data Comm condition ($M = 74.1$ s, $SD = 17.9$) and in the 75% Data Comm condition ($M = 77.6$ s, $SD = 15.7$) compared to the Voice Only condition ($M = 57.9$ s, $SD = 9.1$), $HSD(30) = 11.73, p = .005$ and $p < .001$, respectively. The mean taxi-out duration generally decreased as Data Comm capabilities increased from the Voice Only ($M = 1015.9$ s, $SD = 137.4$) to 40% Data Comm ($M = 982.3$ s, $SD = 83.0$) to 75% Data Comm ($M = 963.8$ s, $SD = 132.3$), although the main effect of Condition was not significant. It is possible that holding aircraft on the ramp longer as a result of data link delays resulted in less congestion on the taxiways. Although the differences in taxi-out duration were not statistically significant, they may be operationally significant and could offset the additional time that aircraft waited on the ramp in the Data Comm conditions. On average, 29 arrivals and 33 departures occurred in each condition. D-Taxi did not affect the duration of taxi-in operations, or the number or duration of delays.

Communications

There was no statistical difference between the number of radio transmissions made from the ground control position to the pilots in the Voice Only ($M = 154.2, SD = 22.0$), 40% Data Comm ($M = 155.7, SD = 18.5$), and 75% Data Comm ($M = 150.6, SD = 22.5$) conditions, but there was a significant effect of Condition for the duration of radio transmissions, $F(2, 30) = 18.67, p < .001$. The controllers made shorter radio transmissions at the ground control position in the 40% Data Comm condition ($M = 4.2, SD = 0.4$) and in the 75% Data Comm condition ($M =$

3.9, $SD = 0.2$) compared to in the Voice Only condition ($M = 4.5$, $SD = 0.4$), $HSD(30) = .25$, $p = .008$ and $p < .001$, respectively. The controllers also made shorter radio transmissions in the 75% Data Comm condition compared to in the 40% Data Comm condition, $p = .021$. Compared to the Voice Only condition, the 75% Data Comm condition saved the controllers about 2.3 min/hr on the radio frequency ($0.6 \text{ s} \times 150 \text{ transmissions} = 90 \text{ s}$ or 1.5 min per 40 min scenario).

There was a significant effect of Condition on the number of radio transmissions from the pilots to the ground control position, $F(2, 30) = 0.88$, $p < .001$. The pilots made fewer radio transmissions to the ground control position in the 75% Data Comm ($M = 187.1$, $SD = 23.6$) condition compared to the Voice Only ($M = 219.6$, $SD = 22.9$) condition and the 40% Data Comm ($M = 206.9$, $SD = 20.2$) condition, $HSD(30) = 17.33$, $p < .001$ and $p = .022$, respectively. There was no difference between the number of radio transmissions made in the Voice Only and the 40% Data Comm conditions.

There was also a significant effect of Condition on the duration of radio transmissions from the pilots to the ground control position, $F(2, 30) = 9.25$, $p < .001$. Radio transmissions were shorter on average in the 75% Data Comm ($M = 2.9 \text{ s}$, $SD = 0.2$) condition compared to the Voice Only ($M = 3.2 \text{ s}$, $SD = 0.3$) condition and the 40% Data Comm ($M = 3.1 \text{ s}$, $SD = 0.2$) condition, $HSD(30) = .16$, $p < .001$ and $p = .019$, respectively. Although these differences are relatively small, they may become operationally significant over time. The pilots reduced their time on the radio frequency by about 1.5 min/hr when 75% of the aircraft were data link equipped compared to the Voice Only condition ($0.3 \text{ s} \times 200 \text{ transmissions} = 1 \text{ min}$ per 40 min scenario). Overall, the 75% Data Comm condition reduced usage of the ground control radio frequency by 3.8 min/hr, or 6.3%, compared to the Voice Only condition.

Workload

Controller workload was unaffected by the use of D-Taxi clearances. Although the controllers' WAK ratings changed between rating intervals, they did not vary between conditions. Either the D-Taxi operations generated as much workload as voice communications or the controllers reallocated the cognitive and physical resources needed for voice communications to other tasks, including the D-Taxi processes.

Point of Gaze

There was a significant main effect of Object on the total duration of looks, $F(4, 60) = 298.63$, $p < .001$. The post hoc analysis showed that the ground controllers looked at the TODDS longer than at any other object, $HSD(60) = 444.52$, $p < .001$, and they looked at the OTW view significantly longer than they looked at the WAK, Local control position, and Miscellaneous objects, all $p < .001$. When the controllers worked at the ground control position, they looked at TODDS for 30 min and 35 s ($M = 1835.0 \text{ s}$, $SD = 112.4$) and at the OTW view for 8 min and 37 s ($M = 517.3 \text{ s}$, $SD = 110.9$) of the 40 min scenario. The controllers spent the remaining 48 s by dividing their visual attention between the WAK ($M = 11.2 \text{ s}$, $SD = 1.2$), Local control position ($M = 23.6 \text{ s}$, $SD = 6.1$), and Miscellaneous objects ($M = 13.12 \text{ s}$, $SD = 2.8$). Even though the controllers used the D-Taxi functions of TODDS in the 40% and 75% Data Comm conditions, they spent the same amount of time looking at the TODDS and OTW in the Data Comm conditions compared to the Voice Only condition.

D-Taxi Usability

We recorded the number and types of actions the controllers performed with the TODDS during each scenario. We then calculated an error rate (ER) for each action type by dividing the number of failed actions (F) by the sum of successful actions (S) and failed actions (F), so that $ER = F/(S+F)$. The overall error rate for the ground control position of the TODDS was 3.3% across all scenarios. Overall, the controllers were able to construct and issue a D-Taxi clearance in only 1.28 s on average, including the time consumed by usability errors.

Controller Opinion

The controllers reported that it took little effort to issue either a canned or user-defined D-Taxi clearance. They reported that it was easy to manage flight data. They had a high awareness of current and projected aircraft positions, potential runway incursions, and the overall traffic situation. Although one controller thought the failed Data Comm indicator was too subtle (“I like the red, but it needs to stand out a little more”), other controllers thought the symbol was “very usable.” Workload due to controller-pilot communications was moderate as was overall workload, but workload at the local control position was slightly higher than workload at the ground control position. The controllers rated the safety of operations at the ground control position as high, but they thought it was less safe at the local control position. The controllers may have been concerned about safety at the local control position because of the complex, busy traffic scenarios that involved intersecting runways.

The controllers thought that D-Taxi would have a positive effect on their ability to control airport traffic. They indicated that it was easier to detect an aircraft deviation if an aircraft had received a D-Taxi clearance ($M = 2.4$, $SD = 1.1$) compared to an aircraft that received a voice clearance ($M = 4.3$, $SD = 2.3$), $t(15) = 3.58$, $p = .003$. However, the controllers did not perceive a difference in the effort needed to manage an aircraft that deviated from its taxi clearance, given the type of taxi clearance. Some controllers thought that D-Taxi may be useful for taxi-in operations, but they did not elaborate on a particular set of procedures that would be likely to work. Others said that D-Taxi for arrivals would be “more challenging” and could result in blocked runway exits and increased pilot workload. Some controllers stated that they would use D-Taxi as much as possible. Others stated that they would not use D-Taxi during rapidly changing weather conditions, during low visibility, during times that the pilot was unfamiliar with the airport, during times that an aircraft had an Expected Departure Clearance Time, or during emergencies. The controllers said that reduced voice communications was one of the greatest benefits of D-Taxi because it reduced the risk of readback and hearback errors, reduced confusion, and improved situation awareness. They thought that the TODDS, as an overall system including D-Taxi, would have a positive effect on the ability to control airport traffic. Although the controllers said that the TODDS had a learning curve that one must overcome before taking full advantage of the tool, they listed a number of benefits, including the fact that it integrates all of the most important information into a single screen. They thought that the TODDS would work in low visibility conditions and that it would improve safety, reduce workload, and reduce the need for verbal communication and coordination.

For complete details of this experiment, see Truitt and Muldoon (2010).

References

- Joint Planning and Development Office. (2007, August). *Next generation air transportation system research and development plan FY 2009-2013*. Retrieved from http://www.jpdo.gov/library/NextGen_v2.0.pdf
- Stein, E. S. (1985). *Air traffic controller workload: An examination of workload probe* (DOT/FAA/CT-TN84/24). Atlantic City International Airport, NJ: Federal Aviation Administration Technical Center.
- Truitt, T. R. (2008). *Tower Operations Digital Data System – Concept refinement and description of new features* (DOT/FAA/TC-08/09). Atlantic City International Airport, NJ: U.S. Department of Transportation, Federal Aviation Administration.
- Truitt, T. R., & Muldoon, R. (2010). *Data Communications Segment 2 Airport Traffic Control Tower Human-in-the-Loop Simulation* (DOT/FAA/TC-10/05). Atlantic City International Airport, NJ: U.S. Department of Transportation, Federal Aviation Administration.