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**Piloting the Future: Design of a Data Link System with Airport Moving Map
for Taxi Operations**

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Mémoire présenté en vue de l'obtention du diplôme de *Maîtrise ès sciences appliquées*

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présenté par **Srishti RAWAL**

en vue de l'obtention du diplôme de *Maîtrise ès sciences appliquées*

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DEDICATION

*To the minds ensuring every safe next destination –
and keeping us far from the Final Destination*

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RÉSUMÉ

Cette étude présente la conception, la mise en œuvre et l'évaluation d'un système intégré de communication contrôleur-pilote par liaison de données (CPDLC) et de carte mobile d'aéroport (AMM) destiné à améliorer la communication, la conscience de la situation et la sécurité pendant les opérations de surface dans les aéroports. La communication par radio, bien qu'omniprésente, est souvent source d'ambiguïté et contribue à la charge de travail mentale, en particulier lors des procédures de roulage non nominales ou sensibles au temps. Le CPDLC offre une alternative numérique en transmettant des autorisations normalisées et préformatées. Associée à l'AMM, qui permet de visualiser graphiquement et en temps réel les itinéraires de roulage, l'intégration qui en résulte est susceptible de réduire considérablement la charge de travail des pilotes, d'améliorer la prise de décision et d'accroître la fidélité des communications.

Dans cette étude, huit pilotes professionnels licenciés ont effectué six procédures de roulage nominales et non nominales dans un simulateur de vol en utilisant soit le système CPDLC-AMM, soit des instructions radio et une carte papier comme référence. Les scénarios ont été soigneusement conçus et divisés en trois groupes fonctionnels : séquençage et priorisation sensibles au temps, réacheminement adaptatif en raison de contraintes opérationnelles et opérations de routine. Chaque participant a été confronté à chaque type de scénario dans les deux modes de communication, dans un ordre contrebalancé afin d'éliminer les effets d'apprentissage.

Les résultats ont montré que le système CPDLC-AMM a permis de réduire la charge de travail par rapport à la condition de référence avec la radio, en particulier en ce qui concerne la gestion des changements inattendus dans les itinéraires et les autorisations, ainsi que l'amélioration de la conscience de la situation. La charge de travail a été évaluée à l'aide du NASA-TLX, et le système intégré a montré des réductions similaires sur les six dimensions, avec des résultats particulièrement notables pour la demande mentale, l'effort et la frustration. La conscience de la situation, mesurée par le SAGAT, était significativement plus élevée lors de l'utilisation du CPDLC-AMM, ce qui indique une meilleure perception, compréhension et projection des situations de trafic. Notamment, la condition de communication radio a conduit à 9 erreurs de navigation sur 24 essais, alors que le CPDLC-AMM n'a conduit à aucune erreur. Ces erreurs étaient

principalement dues à de mauvais virages et se sont produites le plus souvent dans des scénarios impliquant une pression temporelle ou un réacheminement dynamique.

L'utilisabilité du système a été évaluée à l'aide de l'échelle SUS et du questionnaire sur l'expérience de l'utilisateur UEQ. Le score SUS moyen était de 68,12, ce qui indique une facilité d'utilisation acceptable. Les résultats du questionnaire sur l'expérience de l'utilisateur étaient favorables pour les dimensions portant sur l'efficacité, la clarté et la stimulation, tandis que des préoccupations modérées ont été notées en ce qui concerne la fiabilité et l'attractivité de l'interface. Les commentaires des participants ont renforcé les conclusions relatives à la facilité d'utilisation, la plupart des pilotes déclarant que le système était intuitif, facile à apprendre et bénéfique dans les situations de forte charge de travail. Quelques pilotes ont souligné des préoccupations concernant l'augmentation du temps passé la tête basse et le besoin d'ajout d'alertes visuelles en temps opportun.

Dans l'ensemble, les résultats soutiennent la mise en œuvre de systèmes de communication numérique intégrés dans les environnements de cockpit modernes afin de garantir la sécurité, l'efficacité et la croissance des opérations aéroportuaires. Il est important de noter que notre étude est la première à rapporter une charge mentale plus faible lors de l'utilisation du CPDLC-AMM comparativement à la radio durant les scénarios sensibles au temps. Le système CPDLC-AMM développé a démontré des avantages évidents en réduisant les taux d'erreur, en améliorant la conscience de la situation, la charge de travail et de l'expérience de l'utilisateur, en particulier dans les scénarios de roulage non nominaux où les systèmes radio traditionnels ne sont pas à la hauteur. L'étude contribue aux efforts en cours pour moderniser les opérations de surface et fournit un prototype validé qui pourrait être affiné en vue d'un déploiement opérationnel.

ABSTRACT

This study presents the design, implementation, and evaluation of an integrated Controller-Pilot Data Link Communication (CPDLC) and Airport Moving Map (AMM) system intended to enhance communication, situational awareness, and safety during airport surface operations. Radio-based communication, though ubiquitous, often results in ambiguity, increased cognitive workload, and susceptibility to miscommunication, especially during non-nominal or time-critical taxiing procedures. CPDLC offers a digital alternative by transmitting standardized, pre-formatted clearances. When coupled with AMM, which provides real-time graphical taxi route visualization, the resulting integration has the potential to substantially reduce pilot workload, support better decision-making, and increase communication fidelity.

In this study, eight licensed commercial pilots completed six nominal and non-nominal taxiing procedures on a flight simulator using either the CPDLC-AMM system, or radio instructions and paper chart as baseline. The scenarios were carefully designed and divided into three functional groups: time-sensitive sequencing and prioritization, adaptive rerouting due to operational constraints, and nominal routine operations. Each participant experienced each type of scenario in both communication modes using a counterbalanced design to eliminate learning effects and maintain task complexity.

The results showed that the CPDLC-AMM system resulted in lower workload compared to baseline, particularly in managing unexpected changes in routing and clearances, and improved situational awareness. Workload was evaluated using the NASA-TLX, and the integrated system demonstrated consistent reductions across all six dimensions, with especially lower ratings in mental demand, effort, and frustration. Situational awareness, measured through SAGAT, was significantly higher when using the CPDLC-AMM, indicating better perception, comprehension, and projection of traffic situations. Notably, the radio communication condition led to 9 navigational errors out of 24 trials, while CPDLC-AMM led to zero errors. These errors were primarily due to wrong turns and occurred most often in scenarios involving time pressure or dynamic rerouting.

The usability of the integrated system was assessed using the System Usability Scale (SUS) and the User Experience Questionnaire (UEQ). The SUS score averaged 68.12, indicating acceptable

usability. UEQ results were favourable across dimensions like efficiency, clarity, and stimulation, while moderate concerns were noted in reliability and attractiveness. Participant feedback reinforced the usability findings, with most pilots reporting that the system was intuitive, easy to learn, and beneficial in high workload situations, though a few highlighted concerns about increased head-down time and the need for timely visual alerts.

Overall, the findings support the implementation of integrated digital communication systems in modern cockpit environments to ensure safety, efficiency, and scalability in increasingly congested airport operations. Importantly, this is the first study to have shown better performance when using the CPDLC-AMM during time-critical scenarios, compared to radio communication. CPDLC-AMM integration clearly reduced error rates, improved pilot workload ratings, and enhanced SA, particularly in scenarios where radio proved insufficient. The study contributes to ongoing efforts to modernize surface operations and provides a validated prototype that could be further refined for operational deployment.

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LIST OF SYMBOLS AND ABBREVIATIONS

Abbreviation	Meaning
ACARS	Aircraft Communication Addressing and Reporting System
ADS-B	Automatic Dependent Surveillance-Broadcast
AMM	Airport Moving Map
ANOVA	Analysis of Variance
ATC	Air Traffic Controller
ATN	Aeronautical Telecommunications Network
CDTI	Cockpit Display of Traffic Information
CPDLC	Controller-Pilot Data Link Communication
DM	Downlink Message
EFB	Electronic Flight Bag
FAA	Federal Aviation Administration
FANS	Future Air Navigation System
FMS	Flight Management System
HITL	Human-in-the-Loop
ICAO	International Civil Aviation Organization
M	Mean

MFD	Multi-Function Display
NAS	National Air Space
NASA	National Aeronautics and Space Administration
NASA-TLX	NASA Task Load Index
p	p-value (statistical significance)
SA	Situational Awareness
SAGAT	Situational Awareness Global Assessment Technique
SD	Standard Deviation
SUS	System Usability Scale
t	t-statistic (used in t-tests)
TARMAC	Taxi and Ramp Management and Control
T-NASA	Taxi Navigation and Situational Awareness
U	Mann-Whitney U statistic
UEQ	User Experience Questionnaire
UM	Uplink Message
VDL2	Very High Frequency Data Link Mode 2
VHF	Very-high Frequency
η^2	Eta-squared (effect-size)
↑ / ↓	Increase / Decrease (used in summary tables)

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CHAPTER 1 INTRODUCTION

The global air traffic is increasing rapidly, with nearly 2,000,000 flights expected to take-off and land worldwide annually by the mid-2030s [1]. This exponential growth can cause delays in operations at already congested airports [2]. To address this issue, the aviation industry has increasingly opted for advanced communication technologies [3]. One such advancement involves the use of Controller-Pilot Data Link Communications (CPDLC) for taxi navigation. CPDLC is a means of communication between Air Traffic Controller (ATC) and pilots, using data link for communications [4]. These advancements aim to overcome the limitations of traditional radio communications, which have been the primary mode of pilot-controller interaction since the 1950s [5].

Currently, communication relies heavily on Very High Frequency (VHF) radio channels, which function similarly to a conference call where multiple individuals converse over single telephone line. Today, in the radio communication system, all pilots under the jurisdiction of a controller, and an ATC talk over same radio frequency. Radio communications, widely used, are error-prone [6], frequency congested [7], and inefficient. Miscommunications between controllers and pilots require repeated transmissions, leading to wasted communication time, particularly in busy airport environments [5] [8]. Given the limited capacity of radio channels, waiting periods for voice communication are common, since ATC can communicate with only one pilot at a time.

To address the limitations of traditional radio communication such as frequency congestion and miscommunication the aviation industry is increasingly adopting digital solutions like CPDLC. Unlike traditional radio communications that continuously occupy the communication channel, CPDLC optimizes frequency use by exchanging pre-established messages via a Data Link [9]. These messages are displayed as text on a Multi-Function Display (MFD) in the cockpit, as shown in Figure 1.1. Pilots and controllers can send messages using a standardized keyboard. Due to these potential advantages, the Federal Aviation Administration (FAA) recognizes CPDLC as the future of communication in the National Air Space (NAS).



Figure 1.1 Data Link messages displayed on MFD in cockpit

As of today, CPDLC is in various stages of implementation worldwide [10]. It operates using Very High Frequency Data Link Mode 2 (VDL2) with a frequency band of 118 to 136.975 MHz and a data rate of 31.5 kilobits per second [11]. It has two distinct implementations- ICAO's Future Air Navigation System (FANS) and Eurocontrol's Aeronautical Telecommunications Network (ATN). The FANS is an avionics system that provides direct data link communication between pilot and ATC. It has played a pivotal role in the evolution of CPDLC by defining the set of messages that are exchanged. Recently, in 2023, FANS developed its third version, FANS 3/C, to support more responsive communication under high-traffic conditions [6] [12] [13]. This version was introduced to address the incompatibility between previous versions (FANS 1/A), which was designed for oceanic flights, and FANS 2/B, tailored for continental airspace. FANS 3/C resolves this issue by establishing a unified standard and including pre-defined message sets for ground operations, such as taxi clearances and route amendments, as described by the National Aeronautics and Space Administration (NASA) [14]. Similarly, ATN, implemented under Eurocontrol's Link 2000+ program, is the primary data link for the Single European Sky initiative adopted in 2009 [17] [18]. However, the full potential of CPDLC can be realized when integrated with a route visualization system like an Airport Moving Map (AMM) that clearly depicts the taxi route, as depicted in Figure 1.2. An AMM refers to an electronic moving map display of any airport surface, that can directly

enhance Situational Awareness (SA) and reduce the workload of the pilots. The AMM integrates an airport surface map database and ownship position, using data sources like Automatic Dependent Surveillance-Broadcast (ADS-B) to provide real-time updates [17]. By providing better navigation aids to pilots, AMM reduces the chances of runway incursions, ultimately improving efficiency and ground operations [18].

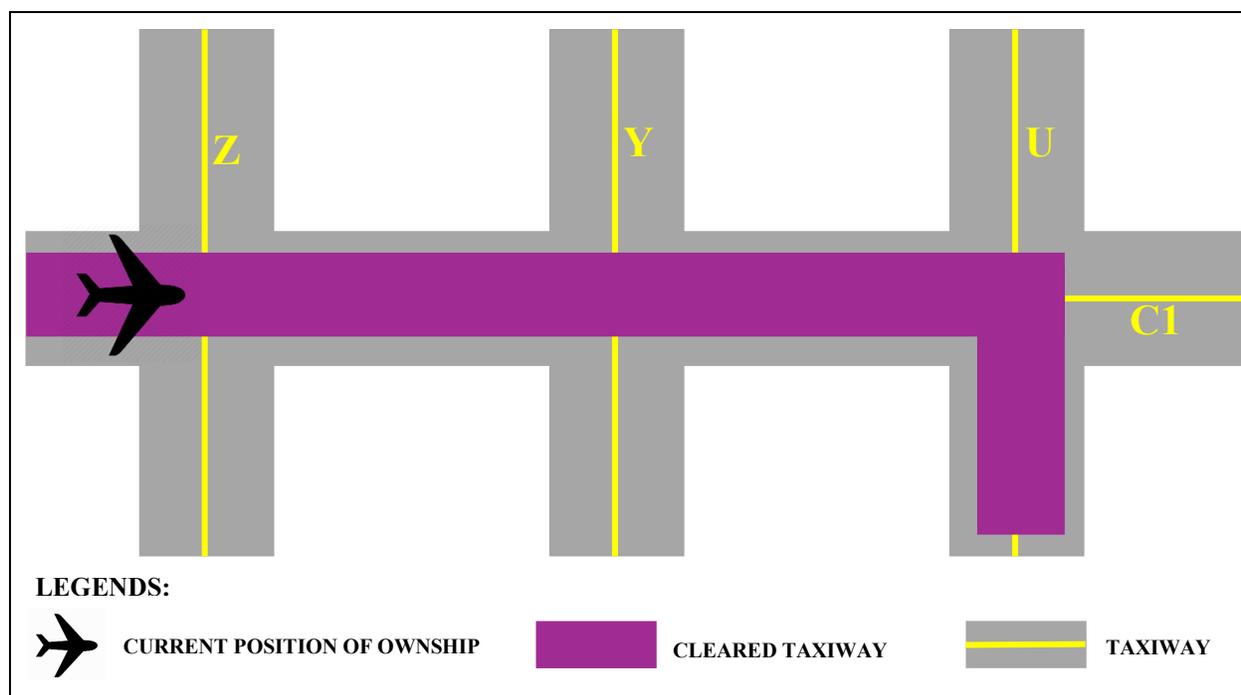


Figure 1.2 Airport Moving Map (AMM)

Despite the advantages mentioned above, CPDLC presents certain challenges. One major limitation is the slower communication loop compared to radio communications, which can cause delay in executing ATC instructions in time-critical scenarios (or non-nominal scenarios). Additionally, using CPDLC for ground operations requires pilots to rely on digital displays, potentially leading to increased “heads-down” time [19]. This could impact their ability to detect hazards or obstacles on the taxiway. Therefore, careful attention must be given to system design and human factors to ensure that CPDLC-AMM integration enhances pilot and ground operations, rather than hindering them [20].

This study aims to design and evaluate a CPDLC-AMM integration tailored for surface operations, with particular attention to cognitive load, SA, and usability. CPDLC with AMM aims to reduce

the risk of miscommunication, such as those caused by poor radio quality or accented language [21], streamline pilot workflows [22], increase SA, and reduce workload during ground operations.

1.1 Objective and Contribution

The objective of this study is to build and empirically evaluate an integrated CPDLC and AMM system for taxi operations, with the goal of determining whether such a system can match or outperform current radio-only procedures. The focus is placed on time-critical, non-nominal scenarios, where communication and decision-making demands are heightened. To achieve this, the study contributes a validated CPDLC-AMM prototype that links clearances directly to route depictions, an experiment that contrasts radio against CPDLC-AMM in both nominal and non-nominal taxi conditions, and evidence on key human performance measures such as workload, situation awareness, communication errors, task efficiency, and usability. Beyond experimental data, the work also develops a taxonomy of communication errors and generates design guidelines for user interfaces and operational practices, specifically addressing how to handle mid-taxi changes and time pressure.

The central research question driving this work is: *In taxi operations, can an integrated CPDLC-AMM system match or outperform standard radio communication—especially in non-nominal, time-critical scenarios?* An extended abstract of this study is currently under evaluation for publication at the AIAA SCITECH 2026 conference

The rest of the thesis is organized as follows. Chapter 2 provides a comprehensive literature review, examining the evolution of communication technology, the benefits and the limitations of CPDLC, along with the role of human factors in system design. Chapter 3 outlines the research methodology, including the framework, data collection methods, and analysis techniques. Chapter 4 presents the results of the study, followed by a discussion of their implications in Chapter 5. Finally, Chapter 6 concludes the thesis by summarizing key findings, discussing limitations, and identifying the scope for future research.

CHAPTER 2 LITERATURE REVIEW

The aviation industry is expanding. Global air traffic is predicted to double from 2015 to the mid-2030s to 200,000 flights per day [1]. This is a challenge for technology improvements to optimize traffic flow, especially at airports already congested with today's traffic. To manage increasing ground traffic and reduce communication bottlenecks, data link systems like CPDLC are increasingly used in en-route and oceanic operations to enhance pilot-controller coordination. CPDLC enables textual data exchange between controllers and pilots, providing an alternative to traditional voice communications. Its increasing use in in-flight operations has generated considerable interest among aviation researchers and professionals [10].

The following literature review addresses the evolution of communication technologies, the benefits and limitations of CPDLC in ground operations, human factors and system design concerns, and directions for future research and implementation.

2.1 Evolution of Communication Technologies

The aeronautical communications began with the allocation of the VHF band in 1947 that had 70 channels originally for mobile aeronautical services [5]. With the rapid growth of commercial jet travel in the late 1950s, particularly following the introduction of jet airliners in 1958, these channels quickly became congested, creating a need for more efficient communication methods. Today, air traffic control still relies heavily on voice transmissions over VHF between pilots and controllers to convey clearances and other flight-critical information. However, with the continued growth of air traffic, this system has reached saturation in many regions during peak operating hours [10].

The radio communications between ATC and pilots can be compared to a conference call. The ATCs and pilots flying in their assigned airspace listen and speak on the same radio frequency. To connect to an aircraft, the ATC names it with an identifier (e.g. AF777) and gives instructions. The pilots must always pay attention to the exchanges on the radio frequency to detect if their identifier is spoken and listen to the instruction given. This increases the interference problems as more active

pilots join the radio frequency [23]. North Atlantic is one of the congested airspace where this similar situation can be seen [20].

The saturation challenges of radio communications are evident when pilots unintentionally talk over an ATC or another pilot during transmission, forcing repeated communication attempts on the same frequency. These problems are especially pronounced in congested airspaces, often requiring the allocation of additional frequencies.

Therefore, communication via datalink is an essential gateway between ATC and pilots. The introduction of the Aircraft Communications Addressing and Reporting System (ACARS) in 1978 was the first major step towards datalink communications, which were further advanced by the FANS committee established by ICAO in 1983 [24] [5]. Its goal was to establish a standardized datalink communication protocol between the ATC and pilots that could replace radio communication.

This initiative ultimately led to the development of CPDLC, a system that revolutionized air-ground communication by allowing predefined digital messages to replace traditional radio transmissions. CPDLC facilitates structured two-way communication, with ATC sending uplink messages (UM) and pilots responding with downlink messages (DM), reducing ambiguity and cognitive effort [9] [4].

ICAO's FANS initiative led to the development of three major versions, to integrate CPDLC across different airspaces, [9] [25]:

- FANS 1/A – Initially deployed in the late 1990s for oceanic airspace and long-haul wide-body aircrafts, this version was developed by Boeing and Airbus (FANS-1 and FANS-A respectively). It relied on ACARS and satellite communications to provide CPDLC where radar coverage was unavailable [26].
- FANS 2/B – An extension of FANS 1/A, it was designed for continental airspace, improving message delivery performance. However, FANS 1/A and FANS 2/B were not interoperable, causing operational inefficiencies.
- FANS 3/C – The latest version, FANS 3/C, has been developed to resolve interoperability issues while also introducing new message sets for trajectory-based navigation (TBO) and

extending CPDLC functionalities to ground operations, including taxi clearances [27] [28] [29].

Beyond en-route navigation, FANS 3/C introduces pre-formatted messages for ground handling, allowing for high-capacity communication in congested airspace [6]. FANS 3/C message set also includes improvements aimed at preventing erroneous actions by pilots [30], such as changes in phraseology (e.g. “BEFORE PASSING” instead of “BY”) and better visibility of conditions (e.g. “AT TIME [time]” instead of “AT [time]”). Using “BY” as a reference position can be easily misinterpreted, especially for people with different first language other than English. The different meanings associated with the word “BY” in various languages may contribute to the predominant error of not beginning the maneuver in time to reach a specified position [31]. This marks a major shift in air traffic management, reducing workload and improving operational efficiency at busy airports [25].

The second implementation called the ATN was implemented in the Eurocontrol “Link 2000+” program and is specified as the main link the Single European Sky rule adopted in January 2009. ATN covers European and continental airspace [15] [16].

CPDLC organizes structured exchanges between ATC and pilots through predefined message sets, ensuring standardized communication and minimizing errors:

- Uplink Messages (UM): Instructions from ATC, including altitude clearances, route changes, and frequency handovers.
- Downlink Messages (DM): Pilot responses such as "WILCO" (will comply) or requests for route modifications [32].
- Clearances: Digital transmission of route amendments, speed restrictions, and other ATC instructions.
- Loadable Messages: One of most significant advancements of CPDLC is the ability to load flight plan clearances directly into the Flight Management System (FMS). This eliminates manual data entry errors, minimizes delays, and allows pilots to execute clearances with a simple confirmation [33] [34].

FANS 3/C's ability to transmit digital taxi instructions directly from ATC to the cockpit enhances efficiency and safety in congested airports [9] [35]. However, integrating CPDLC into taxi operations presents unique challenges. Unlike en-route navigation, modern FMS lacks a "ground flight plan page." While loadable messages function seamlessly for airborne operations, there is no existing mechanism in FMS to integrate taxi clearances directly [36]. To address this limitation, taxi clearances are instead displayed on the AMM or Electronic Flight Bag (EFB), providing a visual reference for pilots. The AMM presents high-definition digital airport maps that displays taxiways, runways, and the real-time position of the aircraft (ownship) as it taxis around the surface. These maps enhance pilot SA by replacing traditional paper-based taxi charts (e.g., Jeppesen charts) with dynamic, real-time navigation instructions. Studies have shown that AMM improves taxi efficiency, reduces navigation errors, and enhances safety during ground operations [18] [37].

As FANS 3/C adoption grows, integrating taxi clearances into AMM will be a game-changer, allowing for automated route visualization, reduced workload, and improved SA [20]. This transition from en-route navigation to ground operations represents a critical step toward fully digitized air traffic management, reducing dependency on voice communication and minimizing errors in high-workload environments.

The advantages of CPDLC are already being seen in operational environments, especially in the United States, where its deployment for departure clearances has made major impact on efficiency and sustainability. In a recent report [38], the FAA's implementation of CPDLC for departure clearances in domestic flights has significantly transformed air traffic management in the US. Though voice communications remain required for tactical and time-critical air traffic control, CPDLC has improved the efficiency, accuracy, and readability of routine communications. This has allowed the achievement of improved controller and pilot productivity, increased airspace capacity, and reduced flight delays. Since its first deployment for departure clearances in 2016 and en route services in 2019, the system has been taken up by 5,900 US-registered aircraft, conserving almost three million minutes of flight time and avoiding more than 41.5 million kilograms of carbon dioxide emissions through avoided taxi delays. CPDLC reduces typical voice communication mistakes to a minimum, diminishing readback/hear-back errors substantially and

generally improving safety. By reducing voice communication use, CPDLC saved over four million minutes of voice radio and reduced approximately three million minutes of airport delays.

The limitations of voice communications are most apparent in heavily trafficked regions, where frequency congestion and inefficiency can lead to critical delays and safety risks [5] [8]. The shift toward digital messaging through CPDLC has improved communication clarity, increased productivity for both pilots and controllers, expanded airspace capacity, and reduced flight delays [5]. However, the transition also introduces challenges, particularly in system interface design and human factors, which must be addressed to realize the full potential of CPDLC [39] [40].

2.2 Benefits of CPDLC in Ground Operations

Research has consistently demonstrated the benefits of integrating CPDLC with AMM for taxi operations. For instance, in 2010, the European commission founded project EMMA to research the Advance Surface Movement Guidance and Control System (A-SMGCS). In the second part of their research called EMMA 2, they introduced CPDLC to issue taxi clearances. They found that datalink, along with AMM improves pilot's SA and reduces workload [22]. The setup was a fixed base simulator equipped with Data Link Communication Unit (DLCU) for sending data messages and Cockpit Display of Traffic Information (CDTI) for AMM. In this study, pilots used DLCU to exchange with tower for *non-time critical clearances* like start-up, pushback, taxi and handover. During scenarios, tower used voice radio to issue time-critical clearances like crossing, line up, and take off. The overall system was operationally feasible and accepted by the participants. Future improvement found by the authors were to have a keyboard or CDU to easily send messages, along with attention getter push-button for better crew awareness when receiving a new tower message.

Similarly, another study with an integrated AMM with ground datalink was tested on a fixed-based simulator with eight pilots [41]. Note that this study used radio communications to request clearances and for non-standard communications, whereas datalink was used to send the clearance and pilot's acknowledgements. This system was highly accepted and appreciated by the eight pilots involved in the study. The navigation performance, safety and finally the graphical representation of the taxi route on the system was acknowledged swiftly by all. Though it was found that the system was very tempting to use, it had positional inaccuracy and increased heads down time.

The benefits of CPDLC are not limited to pilots; controllers also experience reduced workload and improved efficiency. For example, The FAA conducted two 'human in the loop' simulation studies to evaluate the benefits of integrating two-way data link communications with traditional voice radio communications for ground and en-route flight operations [42] [43]. The studies were designed to measure the efficiency of CPDLC under varying levels of aircraft traffic on the ground. The assumption that was included in this study was that the *CPDLC was only used for non-critical scenarios*. For all other critical scenarios voice radio communication was used. Efficiency metrics included flight distances traversed by individual flights, flight times across sector boundaries, and flight delays. The findings indicated reduced workload for the controller and increased SA with the use of CPDLC for ground and en-route operations. Researchers estimated that using CPDLC over radio would increase the number of messages transmitted by controllers by up to 66 percent. The projected annual benefit for the NAS was estimated to be as high as \$337 million [44].

Similar findings were made in [45] wherein 18 airline crew members used data link and Taxi Navigation and Situational Awareness (T-NASA) which is an advanced AMM concept. The airline crew participated in simulated low-visibility taxi scenario using a high-fidelity flight simulator. The crew taxied following the current procedures (voice communication and paper charts) as a baseline and then with future technologies including T-NASA and datalink for clearances along with AMM. Results showed that T-NASA increased taxi speed and reduced navigation errors. The authors also found that datalink for taxi clearances reduced the workload of the crew, but its effects on SA was mixed because of the increased time for crews to react to taxi clearances mid-route.

2.3 Challenges and Limitations

Despite its advantages, the implementation of CPDLC for ground operations faces several challenges. One major limitation is the slower communication loop compared to voice radio, which can delay the execution of time-critical instructions [46] [45]. For example, Etherington et.al. developed autonomous solutions to address the datalink issues in a complex environment with different levels of traffic on the ground. The study used a Multi-Function Display (MFD) for data link communication. Results showed that using datalink during ground operations can be difficult for pilots. The authors simplified the data link system by presenting the taxi messages in a dedicated message area, and provided a set of dedicated buttons to acknowledge and cancel/reject to respond

to ATC messages [19]. This study tested time critical and non-time critical scenarios with twelve pilots. Regardless of the scenarios performed, the workload remained low for datalink. Pilots suggested to add audio alerts to the datalink communication to increase alertness [19].

Another challenge is the potential loss of SA due to greater heads-down time i.e., pilot looking down at the displays as opposed to keeping the head up and looking out the window during taxiing. Jakobi and colleagues conducted a study in Europe to evaluate an onboard taxi guidance system referred to as Taxi And Ramp Management and Control (TARMAC) with ground datalink [47]. The scenarios included taxiing in different visibilities and traffic on the surface that were tested by four commercial pilots. Eye tracking was also recorded for the experiment. All time critical and safety messages were delivered via radio. This study also used advanced features of AMM like indication of clearance by changing the colour of runway to green, yellow or red based on the situation to evaluate pilots' SA. Results showed that the condition using TARMAC and datalink contributed to safer and more efficient ground movements compared to standard paper charts and voice communication, indicating low workload and high SA in low visibility conditions.

One of the major concerns when using CPDLC in ground operations is that pilots must effectively interpret and reply to data link messages without jeopardizing operational performance. In a study by Lorenz & Biella, researchers created an onboard taxi guide system for the improvement of pilots' performance for complex surface operations [48]. Their study compared two conditions: the TARMAC-AS system, which integrates CPDLC, and AMM along with Cockpit Display of Traffic Information (CDTI), and the traditional method using paper charts and voice radio communication. The study involved 49 pilots who performed taxiing scenarios with various visibility and traffic conditions. Results showed that while the system improved navigation accuracy and reduced navigation errors, missed turns, and unnecessary stops, pilots' head-down times were longer, making obstacle detection difficult. Authors simplified the system through the display of taxi messages on a standalone display and the use of soft buttons for acknowledgments. At the end of the study, the pilots emphasized the need of improved audio notifications for SA.

Both voice and datalink communications also face the difficulty in maintaining shared SA between pilots and controllers. Vincenzi et al. recognized the necessity of avoiding conflict between voice commands and flight deck presentation through synchronization of the multichannel information environment [47]. Kerns also addressed this issue and suggested minimizing manual intervention

and employing automatic systems to offer taxi routes, thereby avoiding errors and improving overall efficiency [46].

2.4 Human Factors and System Design

CPDLC's success during surface operations highly depends on system design optimization and careful attention to human factors. Several researchers emphasized the necessity to implement ergonomic interfaces, standardized phraseology, and the integration of decision support tools to reduce mental workload and improve the pilot's SA [39] [49]. Novák and Kováčiková, for instance, emphasized the necessity of system interoperability such as AMM for implementation of CPDLC in ground operations. [40].

2.5 Synthesis

As summarized in Table 2.1, the studies have consistently demonstrated that AMM in combination with Data Link communication is of fundamental benefit to pilots, e.g., improved SA and workload reduction for non time-critical taxi scenarios. Previous research showed that using only datalink communication for ground operation without AMM has no benefit compared to radio.

Subsequent research needs to bridge the knowledge gap by exploring the usability of CPDLC in both time-critical and non time-critical scenarios. This will increase communication efficiency and safety in a wider range of ground operations, particularly in busy airports where taxiing delays are the norm and time-critical communication is required [1] [48]. Additionally, the development of systems that support SA sharing and synchronization between pilots and controllers will be key to successful application of CPDLC to ground operations [5][16]. Such systems will need to overcome the problem of multichannel communication (voice, text, and graphical data) and offer smooth integration without contributing to cognitive load or safety hazards [39] [49].

This research aims to bridge this gap by investigating the full potential of CPDLC in taxiing operations, and its assessment for non-time-critical and time-critical scenarios. In undertaking this research, some observations can be made on CPDLC to drive communication efficiency and safety in surface operations. This is of particular importance to large airports, where multiple taxi delays and the need for fast and secure communications are critical. Solving these problems will ease operations and contribute to the safety and sustainability of aviation.

Table 2.1 Summary of Prior CPDLC-AMM Studies by Scenario, Modality, and Measured Outcomes.

Legend DL: Data Link, Neg: Negatives, SA: Situational Awareness, WL: Workload ↑:Increased/Improved ↓:Decreased/Reduced

Study	CPDLC Format + Map/ Radio used	Scenarios	Number of Participants	Results/ Impact	Observation/Notes
[45]	DL + Radio for emergencies + airport map	Low visibility land-and-taxi scenarios (nominal and non-nominal)	18 crews	Taxi speed ↑, Errors ↓, frequency congestion ↓, WL ↓, SA ↑	Integrate DL w/ T-NASA; reduce delays; Neg: DL-only ↑ action time
[19]	DL + Radio for emergencies	Normal and non-normal procedures, including emergencies and weather changes	12 crews	WL ↓, SA ↑	Improve DL integration w/ audio; Neg: ↑ head-down time
[48]	DL + Radio for time-critical clearances Onboard Taxi Guidance system was used (Tarmac-AS)	Taxi-and-take-off, land-and-taxi scenarios under different visibility and traffic	4 pilots	Voice comms ↓ 75%, SA ↑, WL ↓	Integrate HUDs; Neg: T-AS did not ↑ taxi speed in low visibility
[41]	DL + Radio for clearance request and runway crossings + Graphical representation of airport was used as map	Taxi scenarios with different technology levels (baseline, low-tech, high-tech)	8 pilots	Planning time ↓, navigation ↑; pilots preferred graphical representation	Address complacency risk; improve interface; Neg: ↑ head-down time

Table 2.1 (continued) Summary of Prior CPDLC-AMM Studies by Scenario, Modality, and Measured Outcomes.

Study	CPDLC Format + Map/ Radio used	Scenarios	Number of Participants	Results/ Impact	Observation/Notes
[22]	DL only	Inbound/outbound taxi under different visibility conditions	8 pilots	Safety ↑, WL ↓; graphical clearances ↑ route compliance	Improve CDTI usability; add acoustic signals; Neg: CDTI requires head-down
[46]	DL + airport map	Taxi scenarios with start-up, pushback, taxi clearance, and handover instructions	6 controllers, 8 pilots	Voice comms ↓ 40%, safety ↑, WL ↓	Add acoustic signals; improve route flexibility; Neg: No acoustic signals
[8]	DL + Radio for emergencies + airport map used	NextGen surface operations, including 4DT and equivalent visual operations	Not specified	Communication efficiency ↑, WL ↓; traffic intent ↑ awareness	Develop conflict detection; integrate w/ NextGen; Neg: ↑ head-down time
[48]	DL + Radio for time-critical scenarios + Onboard Taxi Guidance system was used (Tarmac-AS)	Approach, landing, and extended taxiing under varied visibility and traffic density	49 pilots	Navigation errors ↓, unforced stops ↓; no impact on obstacle detection	Integrate HUDs; provide pilot training; Neg: T-AS did not ↑ taxi speed

CHAPTER 3 DESIGN OF CPDLC AND AMM

The integrated CPDLC-AMM system addressed critical challenges within ground operations, such as frequency congestion, miscommunication, and SA degradation. Based on the literature review presented in Chapter 2, this chapter details the design of an integrated system that replaces radio-based taxi clearances with digital messaging and real-time visual guidance. The design prioritizes:

1. Human Factors: Reducing heads-down time and mental workload,
2. Technical Feasibility: Implementing standard FANS 3/C message sets within a functioning CPDLC interface and integrating aircraft position data (from XPlane 11) to support accurate AMM visualization, and;
3. Operational Flexibility: Providing support for both time-critical cases (e.g., rerouting due to obstacles) and non-time-critical scenarios (e.g., routine taxi clearances) as part of the proposed system design.

3.1 Design Principles

The CPDLC system was designed to follow three core principles derived from the literature [40] [50] [51]:

1. User-Centered workflow:
 - Pilots receive CPDLC messages as text-based clearances on a dedicated display reducing reliance on radio communication.
 - AMM visualization (e.g., colour-coded taxiways) is directly linked to CPDLC instructions, reinforcing comprehension and reducing interpretation errors.
2. Minimal Input Burden
 - Pre-defined response buttons (e.g., WILCO, UNABLE) simplify pilot replies.
 - Preloaded taxi clearances reduce manual entry and streamline task execution
3. Real-Time feedback

Emergency changes and reroutes are displayed on the AMM with alert prompts requiring pilot acknowledgment. While the interaction is intentionally minimal, this design choice supports

operational realism by ensuring situational awareness without imposing additional workload during taxi.

The system was developed using a human-centered methodology with emphasis on cognitive ergonomics and operational realism. Evaluation was carried out with pilots using a secondary touchscreen in a fixed-base flight simulator. Interface responsiveness, message clarity, and interaction simplicity were prioritized and refined through iterative testing.

3.2 Human Factors Considerations

Throughout the design process, human factors were a primary driver in shaping both the CPDLC and AMM interfaces. The layout was structured to minimize visual scanning, reduce interaction complexity, and support quick comprehension. Predefined input buttons reduced the need for keyboard interaction, helping to keep the pilot's attention focused on the out-the-window view and primary flight instruments. Message colouring, timestamping, and hierarchical structuring enabled quick prioritization and retrieval of clearances. Furthermore, the dynamic alignment of CPDLC messages with AMM visuals supported mental model consistency, ensuring that textual and graphical representations of taxi instructions were always synchronized. These design elements were intended to lower mental workload, reduce error likelihood, and maintain SA during both nominal and non-nominal surface operations.

3.3 Iterative Design of the CPDLC Interface

The design of the CPDLC interface followed an iterative process grounded in human-centered design principles. The interface was developed in successive stages, starting with paper sketches, then moving to mid-fidelity grayscale wireframes, and finally a high-fidelity prototype—each informed by feedback from aviation human factors experts and formative evaluations.

3.3.1 Paper Sketches

The initial concepts for the CPDLC interface were developed using hand-drawn paper sketches. These early designs focused on enabling pilots to receive and respond to ATC clearances via a

touch interface. The layout included basic components such as the message display area and pilot action buttons for “Accept,” “Reject,” and “Standby.”

However, these first sketches did not include several essential operational features. Elements such as message status indicators (e.g., open, closed), a “Load” button for route visualization, or a structured message log/history view were missing, as shown in Figure 3.1.

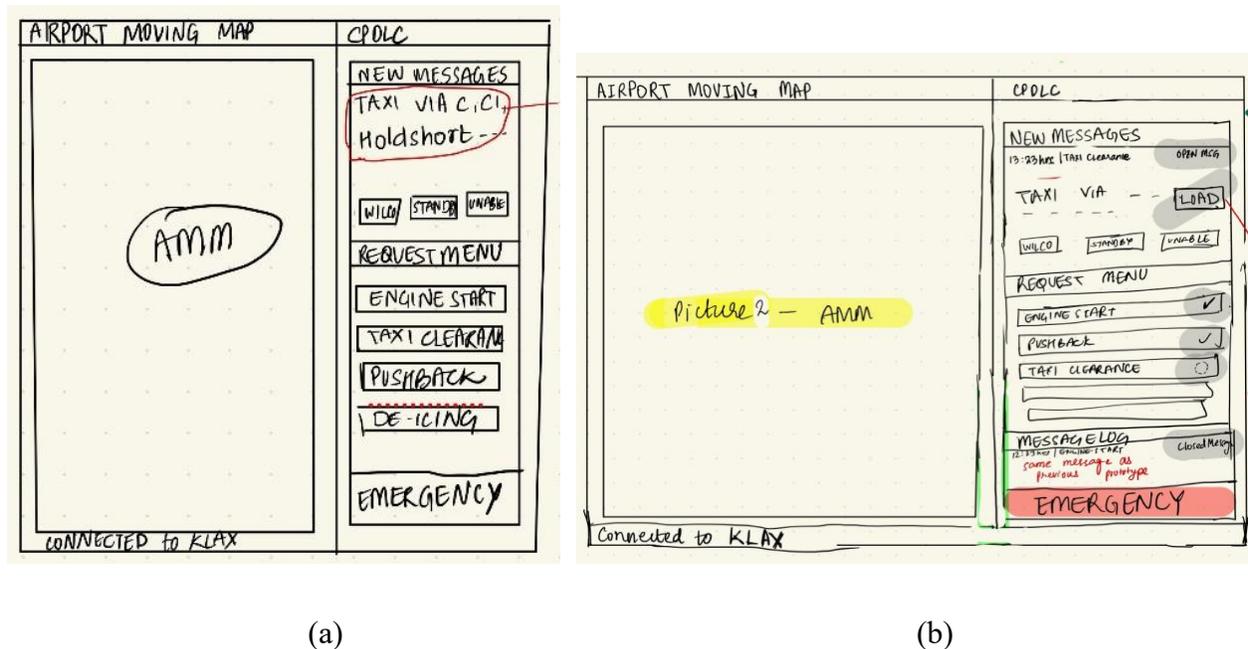


Figure 3.1 Paper sketches illustrating the low-fidelity design evolution of the CPDLC interface.

- (a) Basic CPDLC panel—static new-message area and simple request menu. (b) Enhanced panel—time-stamped entries, “Load” button, message log, and “Open” status label.

After multiple design review sessions with aviation experts and industry partners, and human factors researchers, the interface underwent significant revisions:

- A message status system was added to distinguish pending, acknowledged, and modified messages.
- A dedicated Load button was introduced to allow pilots to preview and validate taxi routes before accepting a clearance.

- The interface was divided into two main sections: a Request Menu for current actionable clearances, and a Message Log for archived communications.
- The layout of pilot action buttons (WILCO, UNABLE, STANDBY, LOAD, EXECUTE, CANCEL) was rearranged based on cockpit ergonomics to minimize selection errors and improve response time (see Figure 3.2)

These changes aimed to improve SA and reduce the chance of overlooking critical instructions.

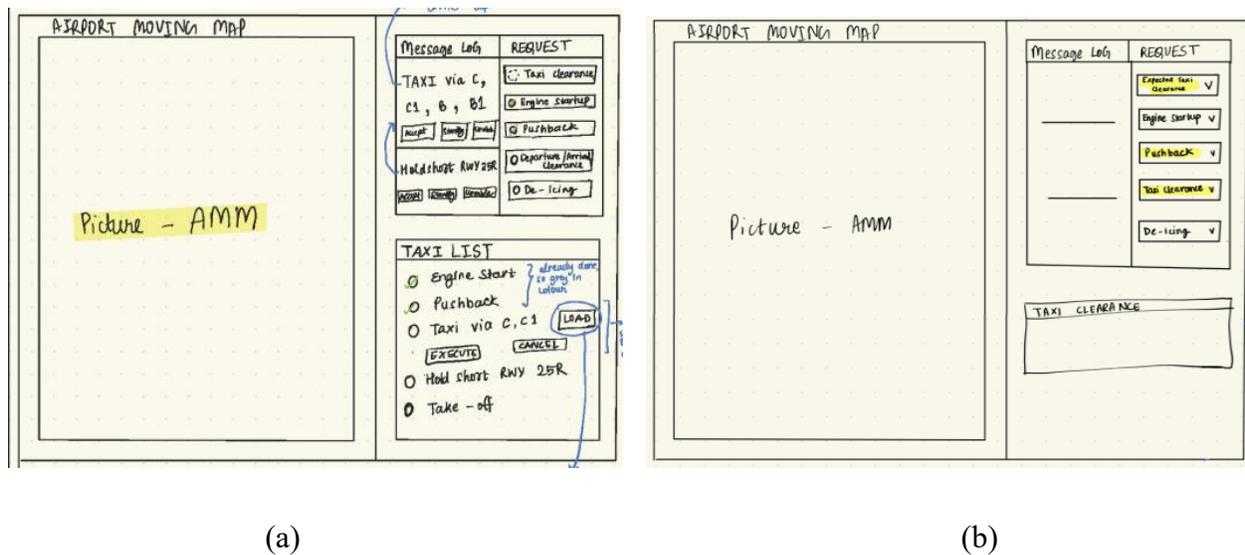


Figure 3.2. Paper sketches illustrating the low-fidelity design evolution of the CPDLC interface. (a) Third version: grouped layout, added a checklist panel and action buttons (Execute, Cancel, Load) with feedback-based annotations. (b) Final sketch: dropdown request categories, clearer section separation, and persistent taxi clearance display.

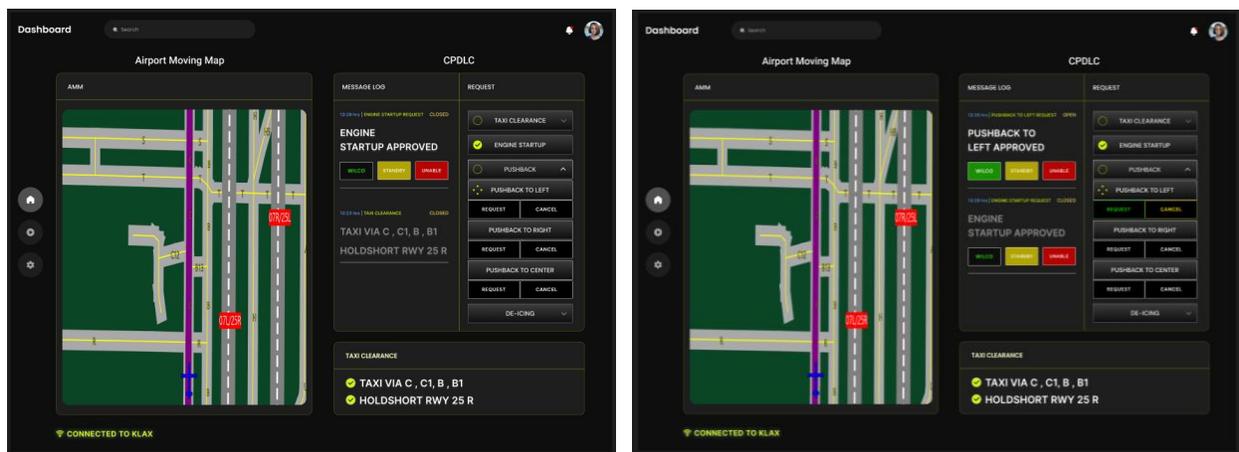
3.3.2 Direct Transition to High-Fidelity Prototype

Following feedback from industry partners and aviation experts during the sketching phase, the CPDLC interface was directly developed into a high-fidelity prototype using Figma¹. Figma is a browser-based interface design and prototyping tool widely used for UI/UX development. It allows real-time collaboration, rapid iteration, and interactive prototyping, which makes it especially

¹ Figma: www.figma.com

useful for designing and testing system interfaces like CPDLC-AMM. While a separate grayscale wireframe phase is often used in traditional design processes, this step was omitted in favor of accelerating the testing and iteration cycle. To ensure layout and functional grouping were still thoroughly evaluated before styling decisions, early versions of the Figma design were initially reviewed with color removed to assess visual hierarchy and spacing.

The high-fidelity prototype featured a structured three-panel layout: Message Log, Request Panel, and Taxi Clearance Summary, building on feedback from earlier iterations. Status tags (e.g., OPEN, CLOSED) with color codes were reused to support rapid comprehension. Action buttons were color-coded and spatially separated to minimize selection errors, see Figure 3.3.



(a)

(b)

Figure 3.3 Screenshots of the high-fidelity CPDLC prototype showing various interface states. (a) CPDLC panel displaying an approved engine startup clearance with structured status indicators and message acknowledgment options. (b) Approved pushback clearance and corresponding AMM route update with dual clearances visible in the Message Log.

Dropdowns for each request type reduced interface clutter, allowing pilots to navigate options without crowding the interface. The Pushback menu included directional choices (Left, Right), in Figure 3.4-a. LOAD and EXECUTE buttons synchronized with AMM route preview and activation, see Figure 3.4-b. This functionality provided a strong alignment with common FMS behavior, reinforcing familiarity and minimizing cognitive friction.

The resulting prototype served as the final testbed for usability evaluation during the human-in-the-loop (HITL) simulations described in Chapter 4. It incorporated all key learnings from the low-fidelity design phase and was tailored for operational realism in a touchscreen cockpit setting.



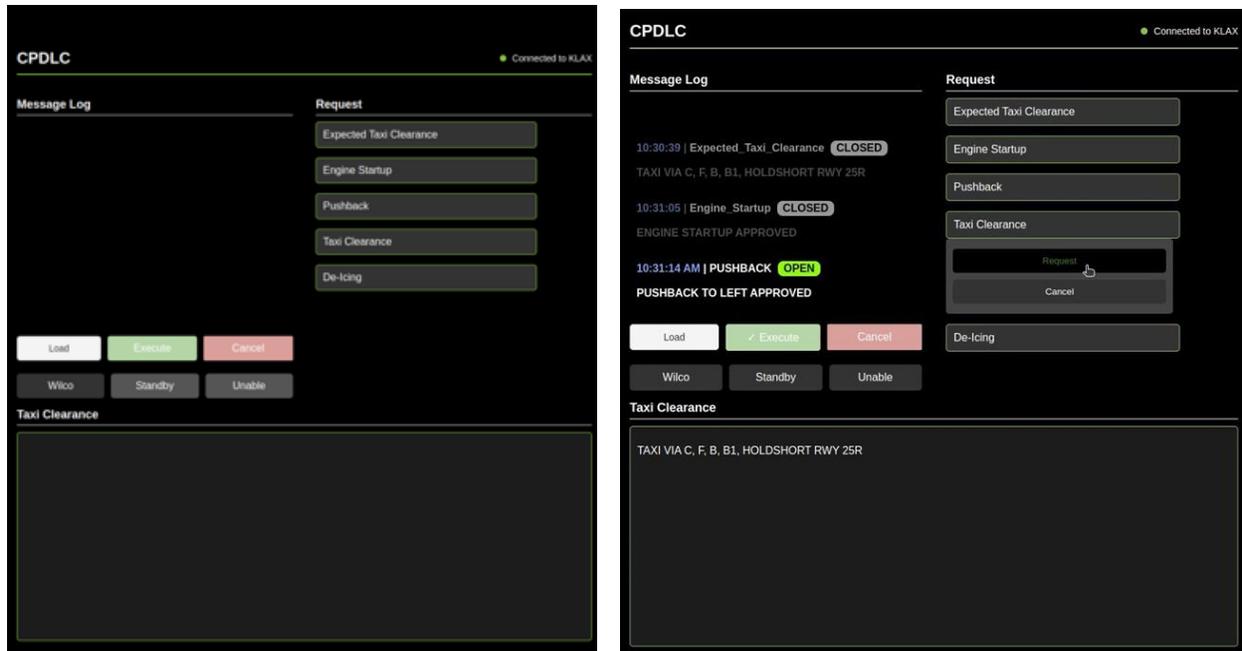
Figure 3.4. Screenshots of the high-fidelity CPDLC prototype showing various interface states. (a) Pushback sub-menu illustrating directional choices (Left, Right) and active selection feedback (highlight). (b) Expanded Request Panel with dropdown sections and contextual buttons for taxi clearance, pushback, and de-icing

3.3.3 Flask-Based Implementation of the CPDLC Interface

To support realistic interaction and enable system integration with the simulator, the final CPDLC interface was implemented using Python Flask, a lightweight web framework suitable for rapid prototyping and deployment. This version translated the Figma-based high-fidelity prototype into a functioning, interactive interface that could respond to pilot inputs, simulate ATC messages, and trigger visual feedback dynamically. Figure 3.5 presents a screenshot of the Flask application used in the study.

The Figma layout was preserved with dark mode and a three-panel structure. Each message was rendered with an associated timestamp and an “OPEN” or “CLOSED” tag to reflect its current status. Pilot inputs were managed using a two-row button layout, mirroring the functional separation established in the prototype. Predefined ATC and operational buttons mirrored the FANS interface and enabled route management.

The Request Panel supported procedural requests across multiple categories (e.g., Taxi Clearance, Pushback, Engine Start), with each request expandable into context-specific options. For instance, selecting Pushback opened a submenu allowing pilots to choose the pushback direction (Left or Right) or to highlight the anticipated route on the map. All selections triggered corresponding changes in both the interface and backend data, managed through Flask route logic and JavaScript-based interactivity.



(a)

(b)

Figure 3.5 Flask-based CPDLC interface. (a) Interface with active buttons and categorized request options, shown prior to any message exchange. (b) Updated interface with time-stamped ATC messages, message status labels, active request interaction, and taxi clearance display.

This implementation allowed the interface to be tested in human-in-the-loop simulation trials, where it served as the operational front-end for CPDLC communication. It enabled a realistic interaction experience, as the entire message exchange and acknowledgment flow could be dynamically tested, simulating live cockpit behavior.

The final CPDLC interface displayed standard FANS 3/C-formatted clearances in a structured message log, supported immediate pilot responses via predefined action buttons, and was directly

linked to the AMM to reflect accepted or modified taxi routes. This integration enabled pilots to quickly access instructions and visually confirm compliance, minimizing ambiguity during taxi operations.

In summary, the Flask application provided a testable and scalable version of the final CPDLC design. It supported interface responsiveness, real-time feedback, and route visualization features critical to the experimental scenarios outlined in CHAPTER 4.

3.4 Iterative Design of the AMM Interface

The AMM used in this study was originally developed in JavaFX by a doctoral student from McGill University as part of an independent project. While the base application was pre-existing, its visual behavior and interactive logic were iteratively refined to align with the CPDLC interface, human factors principles, and operational needs.

3.4.1 Initial Versions and Limitations

The initial version of the AMM displayed a static layout of the airport surface, including labeled taxiways, runways, and hold short points. It provided real-time tracking of ownship position using telemetry data from the X-Plane simulator but lacked several key features. There was no visual representation of CPDLC-issued clearances, no route overlays, and no rerouting notifications, see Figure 3.6. As a result, pilots had to mentally map text instructions to the surface layout without spatial guidance, increasing cognitive load and the risk of misinterpretation.

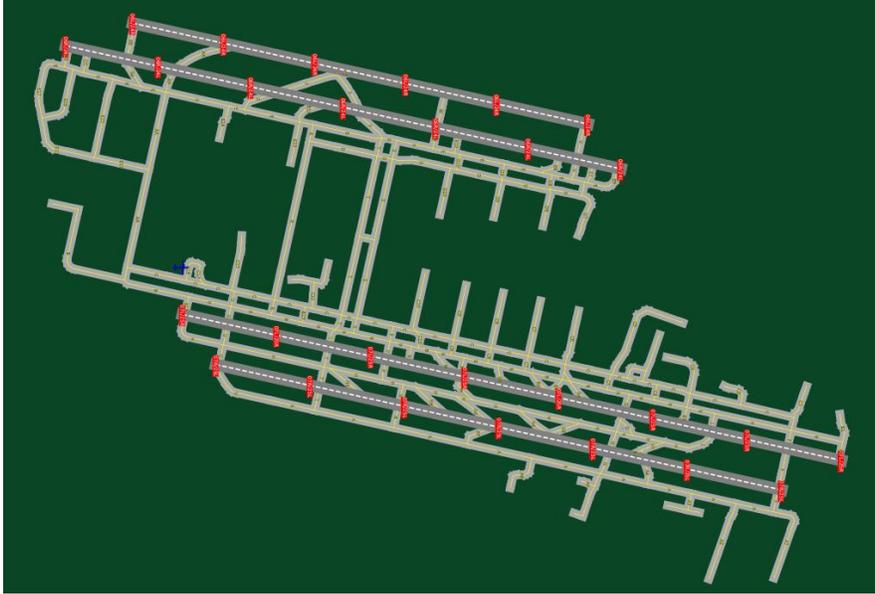


Figure 3.6 AMM designed in JavaFX, centered around real-time ownship position and updated based on X-Plane telemetry.

3.4.2 Route Visualisation and Rerouting Alerts

In collaboration with academic researchers and industrial experts, several enhancements were made to the AMM to support route visualization and rerouting feedback. A synchronized color-coded overlay system was implemented to reflect the status of the taxi route based on pilot actions within the CPDLC interface:

- Dashed magenta line: Displayed when a taxi clearance was loaded by the pilot for preview using the LOAD button but not yet executed (Figure 3.7).
- Solid magenta line: Shown after the pilot executed the loaded clearance using the EXECUTE button, marking it as the active route to follow (Figure 3.8).
- Solid yellow line: Used to indicate outdated or canceled segments of a previous clearance, especially when a reroute was issued (Figure 3.9).

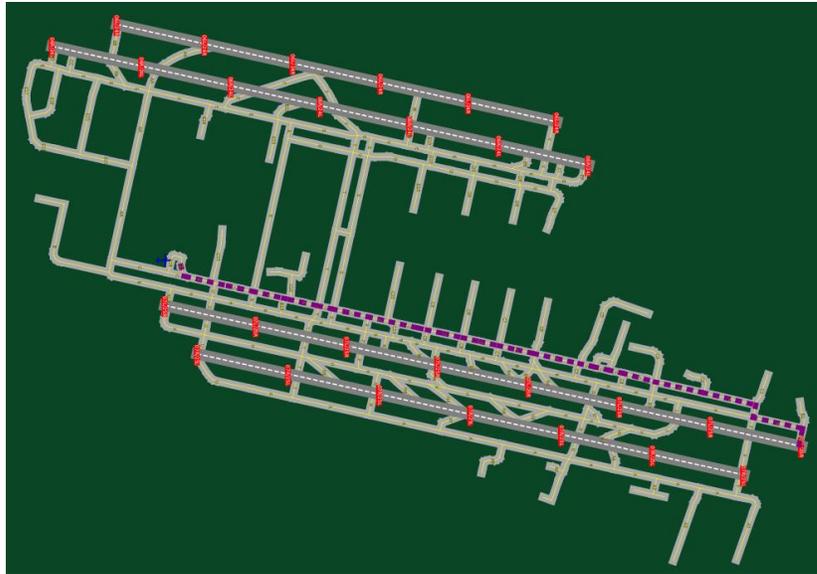


Figure 3.7 Dashed magenta line- Preview of loaded taxi clearance

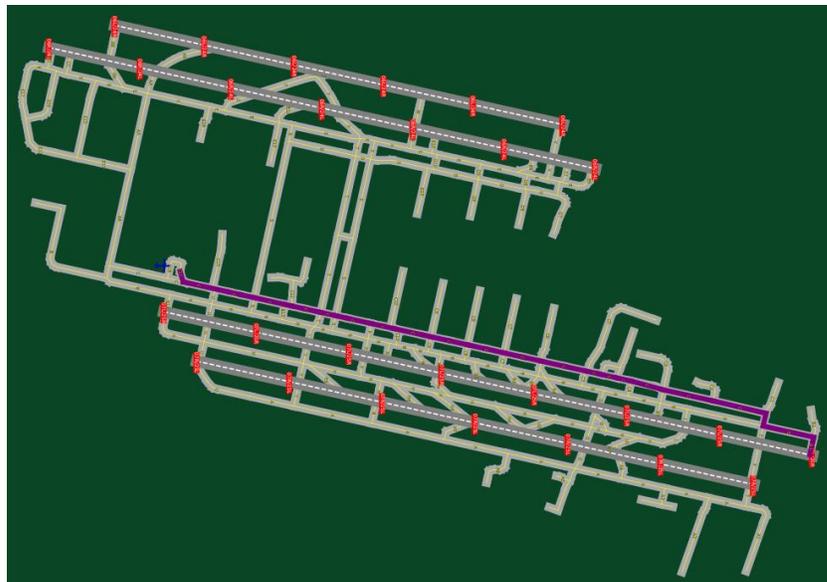


Figure 3.8 Solid magenta line- Active taxi route after execution

These visual elements were dynamically generated and updated in real time based on pilot interactions, providing immediate and intuitive spatial feedback.

To accommodate non-nominal taxi situations, such as dynamic rerouting due to traffic conflicts or taxiway closures, a route change alert system was introduced. When a revised clearance was issued,

the AMM displayed a pop-up near the aircraft symbol, prompting the pilot to review the new route (Figure 3.9). The updated path appeared as a dashed magenta line. Once the pilot confirmed by pressing EXECUTE, the new path was displayed as a solid magenta line and the outdated path was rendered in yellow.

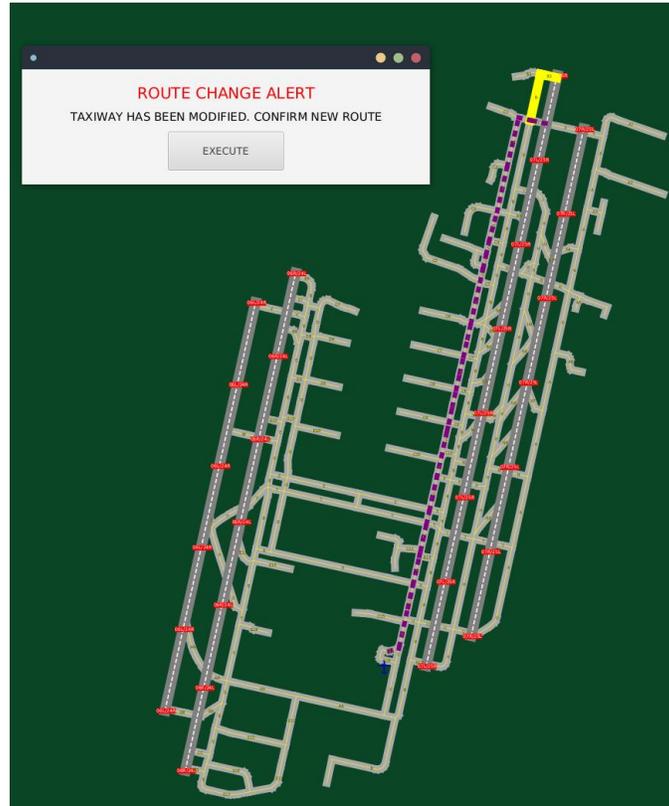


Figure 3.9 Solid yellow line- Outdated or canceled route segments after rerouting

3.4.3 Final Integration and Evaluation

The finalized AMM interface, shown in Figure 3.10, was integrated with both the CPDLC panel and the simulator environment via the Ingescape platform. It processed real-time telemetry, supported message-triggered route drawing, and updated the display in response to pilot inputs and ATC clearances. Specifically, the system enabled:

- Route highlighting and dynamic confirmation
- Mid-route reroute alerting and validation

- Visual feedback for clearance execution
- Real-time ownship tracking

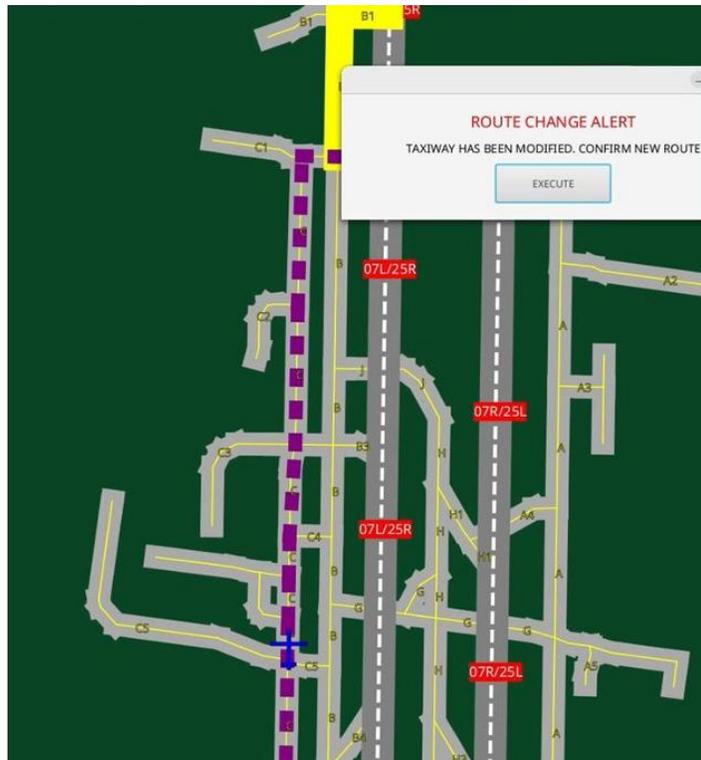


Figure 3.10 Final AMM layout showing the aircraft position in dark blue, alert pop-up overlay and updated taxi path in response to route change.

This integration allowed the AMM to support the pilot's SA and to act as a communication-confirmation interface during taxi operations. It played a central role in reducing workload and supporting pilots in adapting to evolving ground traffic conditions.

3.5 Ingescape Platform

To support real-time communication between system components, the CPDLC-AMM system was integrated using Ingescape Circle, a visual programming platform for interactive prototyping. This architecture enabled seamless data flow between the CPDLC interface, AMM, and the X-Plane flight simulator, allowing each module to operate independently while remaining fully synchronized.

As shown Figure 3.12, three key Ingescape nodes were implemented:

- Pilot_CPDC_APP: Manages CPDLC messages, pilot responses, and procedural requests. It also receives clearance messages sent directly via Ingescape, such as clearances triggered by scenario conditions, as shown in Figure 3.11.
- Aircraft_Agent: Streams live telemetry from the X-Plane simulator, including position, heading, brake status, and speed, enabling real-time ownship tracking, as shown in Figure 3.12 (a).
- AMM: Displays a geo-referenced airport layout and overlays route visuals (dashed, solid, yellow) based on CPDLC messages and pilot inputs, as shown in Figure 3.12 (b).

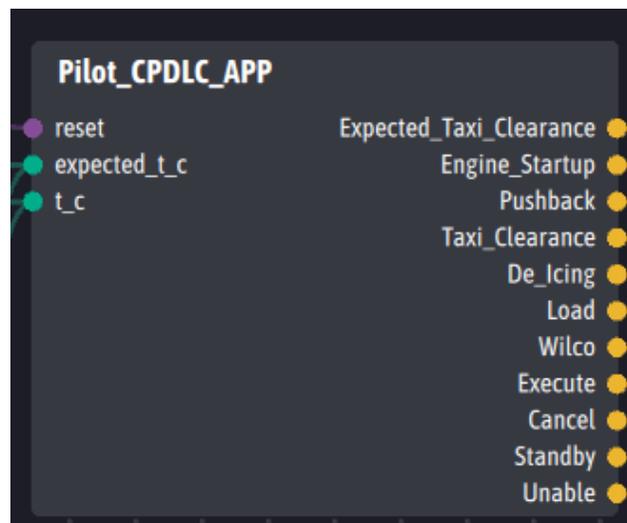


Figure 3.11 Pilot_CPDC_APP: Manages CPDLC clearances, responses, and requests linked to AMM.

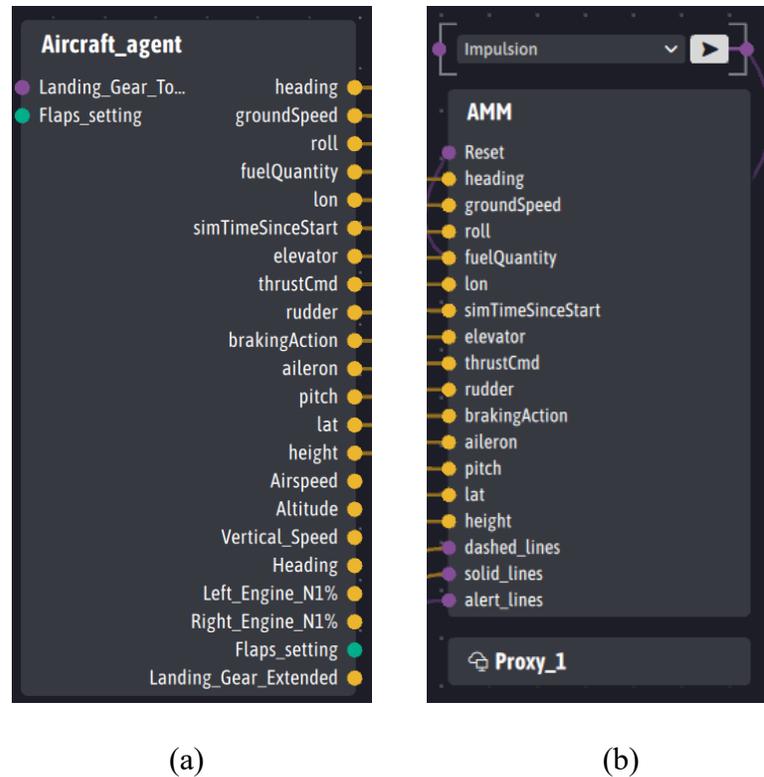


Figure 3.12 Ingescape platform showing CPDLC-AMM-simulator integration. (a) Aircraft_Agent: Streams real-time X-Plane telemetry for AMM updates. (b) AMM: Displays route overlays (dashed, solid, alerts) based on CPDLC and scenario inputs.

In Ingescape, each module is treated as a node (or “brick”) connected by visual links. For example, when a pilot presses LOAD or EXECUTE on the CPDLC panel, the Pilot_CPDC_APP node transmits the command to the AMM node, which immediately updates the displayed route. Likewise, reroute messages were sent via Ingescape to the CPDLC and AMM applications and displayed with minimal latency, as shown in Figure 3.13.

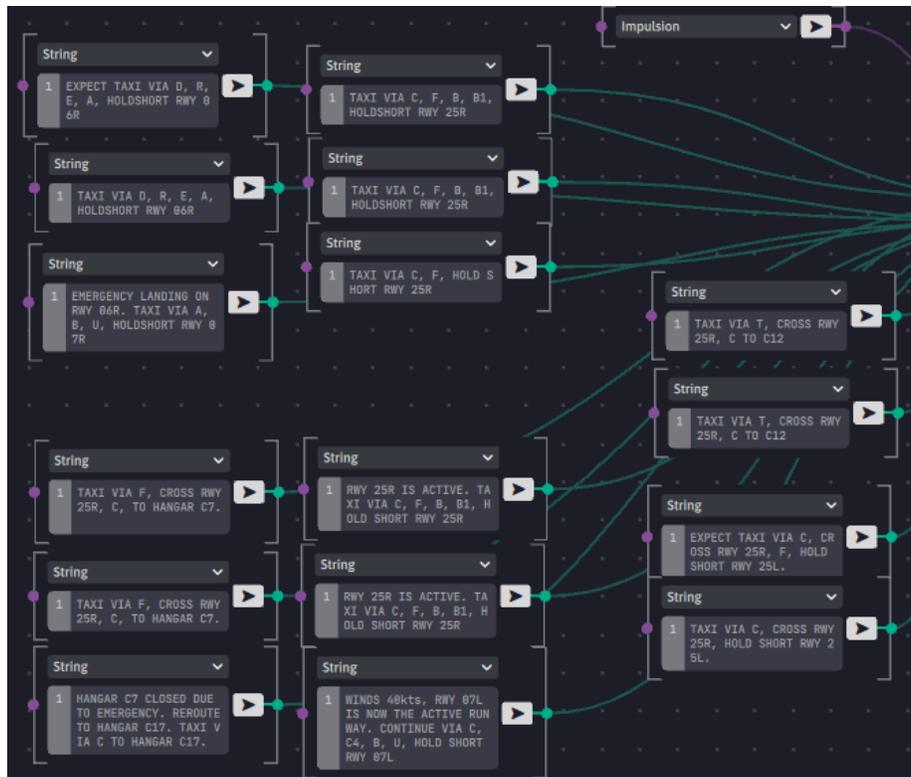


Figure 3.13 CPDLC messages sent and logged within the simulation.

This flexible architecture allowed dynamic adjustments during development and testing, ensuring full synchronization across modules. Pilot actions, route states, telemetry feedback, and time-critical updates were consistently aligned across systems throughout the experiment.

3.6 Integration of CPDLC-AMM

Figure 3.14 illustrates the final integrated CPDLC-AMM system as deployed in the simulator environment. On the left, the AMM displays the assigned taxi route over a geo-referenced airport map. The route is updated dynamically based on pilot interaction with the CPDLC panel.

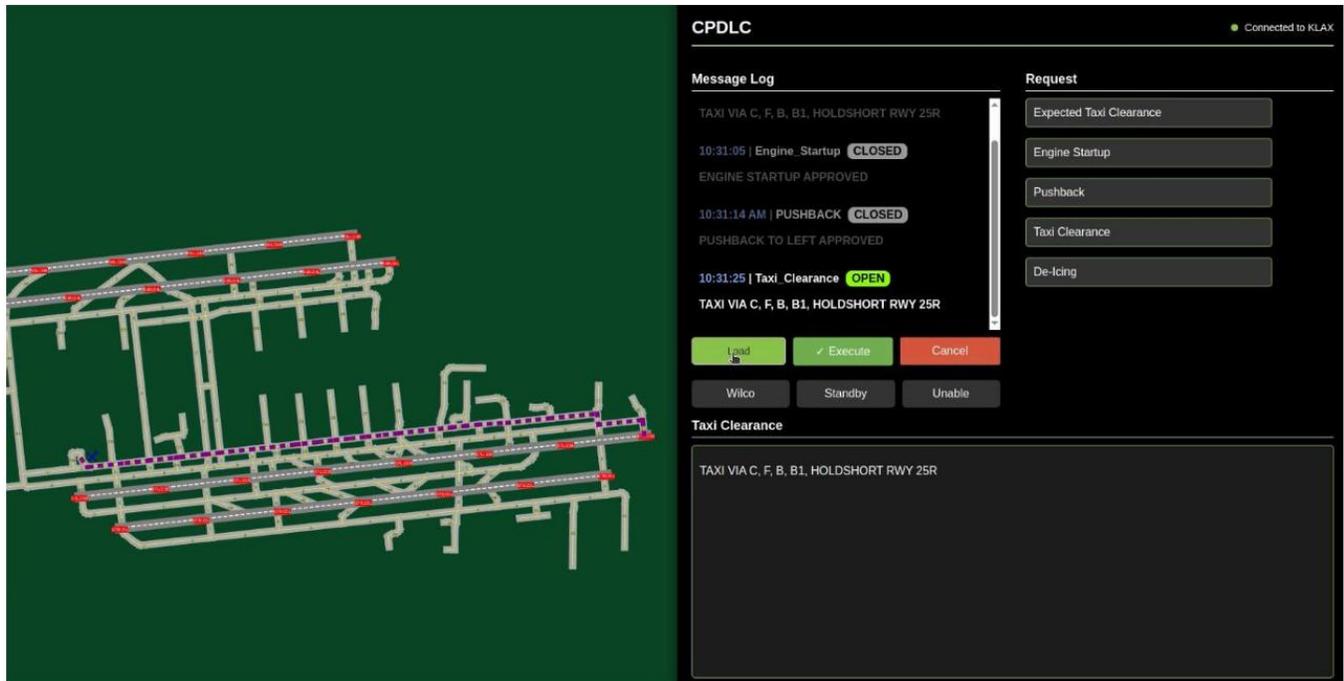


Figure 3.14 Fully integrated CPDLC-AMM system deployed in pilot experiments, showing coordinated message interaction and live route feedback via AMM.

On the right-hand side, the CPDLC interface contains three structured areas: a scrollable Message Log, a Request Menu, and a persistent Taxi Clearance display. Messages are tagged as OPEN or CLOSED, and interaction options allow pilots to respond or manage the clearance.

The CPDLC-AMM system integrated all prior design elements into a unified interface, enabling real-time coordination of message handling, route previews, clearance execution, and reroute confirmations. This final version was used in the human-in-the-loop trials with commercial pilots, as described in Chapter 4.

CHAPTER 4 METHODOLOGY

4.1 Overview/Study Design

This study involved human-in-the-loop (HITL) simulation with a mixed-method approach to evaluate the integration of the CPDLC and an AMM for surface taxi operations. The research design combined quantitative (e.g., error rates) with objective (e.g., SA) and subjective assessments (e.g., workload) to assess the system's efficacy in both time-critical (non-nominal) and non-time-critical (nominal) scenarios.

The baseline for comparison replicated current day operational practices. At present, the operations of the surface of the airport are conducted using a paper map and/or Electronic Flight Bag (EFB) with apps like ForeFlight², and clearances that are given over the radio by the ground controller. The pilots rely on cockpit instruments to monitor the aircraft's speed and heading. In this baseline condition, no integrated AMM or datalink communication system was used.

4.1.1 Objectives

To systematically address the research problem and evaluate the proposed system's effectiveness from a human factors perspective, the study was guided by the following key objectives:

- Design and evaluate an integrated CPDLC-AMM system for ground taxi operations to address limitations of traditional voice-based communication, especially under high workload or time-critical scenarios.
- Assess pilot cognitive workload in both non-nominal (time-critical) and nominal (non-time-critical) taxi scenarios when using CPDLC-AMM, relative to baseline radio communication, using NASA-TLX scores as the primary metric.
- Measure pilot SA across different communication modes using the SAGAT method, identifying differences in perceptual and cognitive task performance.

² ForeFlight: <https://foreflight.com/>

- Quantify communication efficiency by analyzing objective task metrics such as error rates and response times in CPDLC-AMM versus traditional radio-based conditions.
- Evaluate usability and user experience of the CPDLC-AMM prototype using standardized instruments like the System Usability Scale (SUS) and User Experience Questionnaire (UEQ).
- Identify implications for operational adoption, including recommendations for interface refinement and procedures to support integration into real-world aviation environments.

4.1.2 Hypothesis

This study evaluates the following hypotheses, grounded in prior research on datalink systems and human factors in aviation [19] [22] [45].

Primary Hypotheses:

H1: Pilots using CPDLC-AMM integration will exhibit lower cognitive workload when compared to traditional voice radio communications, as measured by NASA-TLX scores.

H2: Pilots using CPDLC-AMM will demonstrate higher SA during taxi operations, evidenced by higher SAGAT scores and reduced navigational errors.

H3: Pilots using CPDLC-AMM will demonstrate reduced communication errors (e.g., misheard clearances) compared to baseline, quantified via screen recordings.

Secondary Hypotheses:

H4: Time-critical scenarios will yield greater workload reduction benefits with CPDLC-AMM than nominal scenarios.

H5: System usability (SUS) and user experience (UEQ) will be positively rated for CPDLC-AMM during taxi operations.

4.2 Participants

This study recruited eight participants holding either a valid Commercial Pilot Licence (CPL) or Airline Transport Pilot Licence (ATPL). Their ages ranged from 31 to 57 years, with an average age of 47 years. All participants had completed higher education, including bachelor's, master's,

or doctoral degrees. Their aviation experience varied between 11 and over 21 years, with most having accumulated more than two decades of professional flying. The recorded total flight hours spanned from approximately 1,025 to 16,500 hours, with a group average of 5,656 hours. Participants reported operational familiarity across a variety of airport environments, including corporate, commercial/regional, and international airports. Familiarity with CPDLC ranged from “somewhat familiar” to “very familiar,” suggesting moderate to extensive prior exposure to data link systems. Regarding the equipment used for taxi operations, all participants had experience with electronic flight bags (EFBs), electronic airport charts, and dynamic AMM, while 5 out of 8 participants also reported prior use of printed airport charts. This varied background ensured that all participants were well-positioned to evaluate both traditional and advanced taxi communication systems.

4.2.1 Recruitment and Compensation

Pilots were recruited via professional networks (e.g., through ADAIR partners) and word-of-mouth referrals. Each participant received \$50 compensation and a parking ticket for on-site sessions, acknowledging their time commitment (~3 hours per session).

4.3 Apparatus and Setup

The participants were seated in the simulator of airliner cockpit in the premises of Polytechnique Montreal (see Figure 4.1). This is a 2-seat, fixed base simulator using X-Plane 11 as the flight simulation software. The external view is projected on 5 large screen monitors in front of the pilots. Three head down displays are used for the flight instruments and navigation. In our study, we clamped a touchscreen monitor in front of the participants to display the AMM and CPDLC application for taxi navigation.



Figure 4.1 Flight simulator at Polytechnique with a touchscreen monitor clamped to display CPDLC with AMM

A simplified taxiing model of Cirrus Vision Jet, a single-engine light jet was used for taxiing on the surface of Los Angeles International airport (KLAX).

4.4 Scenarios

To evaluate the effectiveness of the integrated CPDLC-AMM system compared to traditional radio communications, six realistic airport taxi scenarios were developed and tested through a HITL simulation. These scenarios reflected a range of operational conditions encountered during surface operations at busy airports, including both time-critical (non-nominal) and non-time critical (nominal) scenarios. Based on their underlying characteristics, the scenarios were organized into three functional groups, as shown in Figure 4.2, each designed to test pilot's workload, SA, and communication performance.

Importantly, as part of each functional group, a pilot would test one scenario using CPDLC and the other scenario using radio. This order was reversed for the next participant. For instance, if

Participant 1 performed Scenario 1 (emergency hold) via radio and Scenario 3 (departure sequence) via CPDLC, then participant 2 would receive Scenario 1 via CPDLC and Scenario 3 via radio. This counterbalanced design ensured fairness, avoided learning effects, and preserved the complexity of tasks across participants.

Great efforts were invested in ensuring ecologically valid scenarios that are of comparable complexity and urgency within a group. We consulted with 2 tower operators over a month to select the disturbance events and write the proper clearances. We also obtained the feedback from 2 airlines pilots to confirm that the two scenarios within the same category are of similar difficulty while being different to prevent learning effect. The six scenarios are described next.

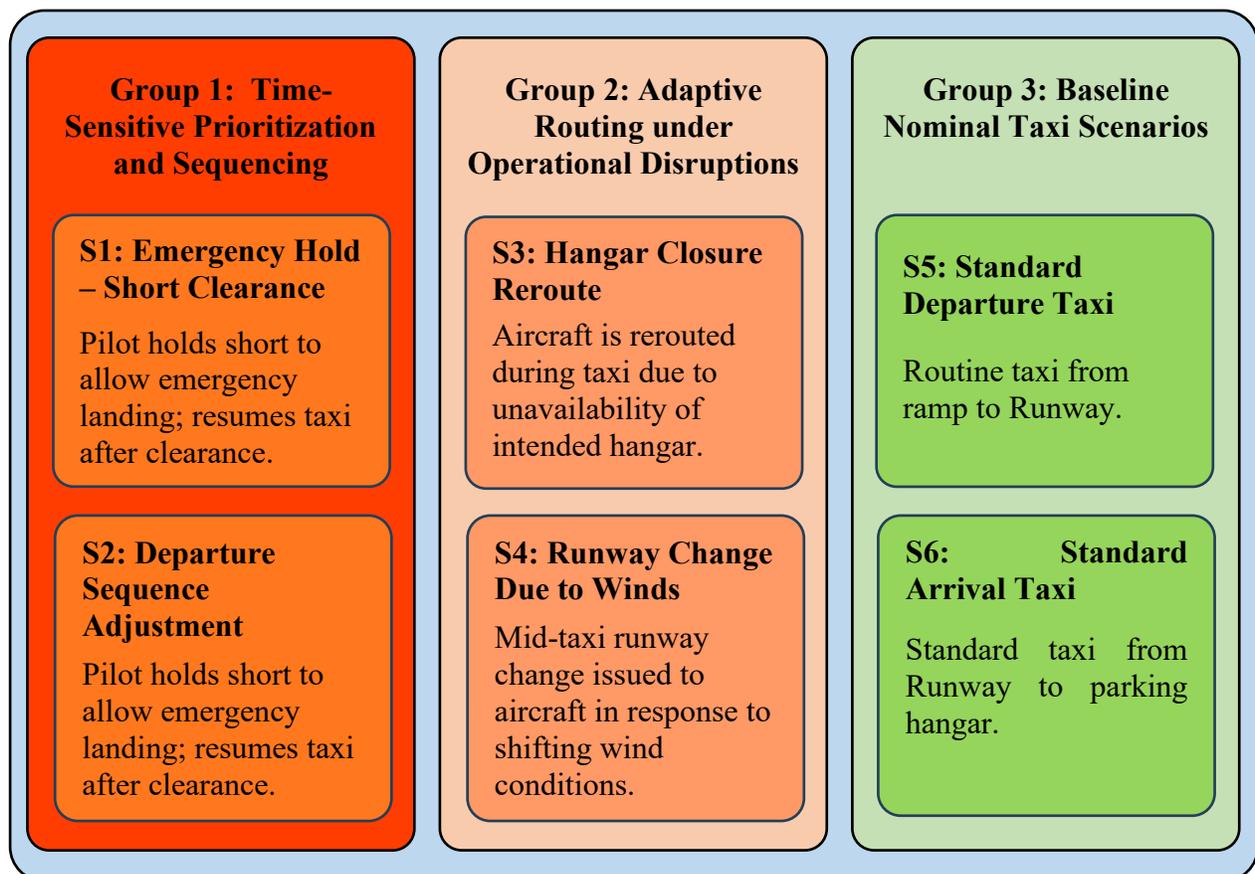


Figure 4.2 Scenarios tested during the study

4.4.1 Group 1 Time-sensitive

The first group of scenarios, Scenario 1 and Scenario 2, focused on operational complexities involving aircraft prioritization and sequencing in time-critical (non-nominal) scenarios. Scenario 1 involved a hold-short instruction issued to an aircraft waiting for an emergency landing on the same runway. Scenario 2 presented a departure sequencing challenge where two aircraft had to be managed for takeoff from different points, requiring ATC to revise the order based on external factors. These scenarios tested the pilot's responsiveness and SA in dynamically changing yet safety-critical environments.

4.4.2 Group 2 Adaptive Routing

The second group, Scenario 3 and Scenario 4, centered around dynamic taxi route changes triggered by external operational causes. In Scenario 3, an aircraft originally cleared to taxi to a specific hangar was rerouted due to an unexpected closure, requiring the pilot to follow an alternate path. Scenario 4 simulated a runway change mid-taxi due to shifting wind conditions, compelling ATC to issue a new clearance on the fly. These scenarios challenged the systems and pilot's adaptability to sudden changes in the environment.

4.4.3 Group 3 Nominal Taxi

The third group, Scenario 5 and Scenario 6, represented standard arrival and departure taxi scenarios, used as baselines to compare with the more complex, non-nominal conditions. Scenario 5 simulated a routine departure from ramp to runway, while Scenario 6 involved a normal arrival taxi path from the runway to a designated stand. These nominal conditions provided a reference point to evaluate the effectiveness, workload, and SA in simpler, predictable contexts.

4.5 Data Collection

We compared the two communication modes by measuring the participant's SA, workload, and adherence to the taxi clearance. We also measured the perceived usability of the CPDLC-AMM applications. These measures are described next.

4.5.1 Situational Awareness (SA)

SA is the knowledge relevant to the task being performed and it is a critical input to decision-making. Endsley's enduring definition of SA is "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future" [47]. In the context of taxi navigation, this means that pilots need to be aware of the aircraft's position on the taxiway, the proximity of other aircraft or vehicles, and the current ground traffic conditions.

For example, when approaching an intersection during taxiing, a pilot must perceive their own position on the taxiway and the presence of surrounding traffic such as a maintenance vehicle nearby (Level 1: Perception). Next, the pilot must comprehend whether the maintenance vehicle's position poses a potential hazard to continued taxiing (Level 2: Comprehension). Finally, the pilot must project that the vehicle is likely to clear the taxiway shortly, allowing them to safely resume taxi without intervention (Level 3: Projection).

Endsley's model of SA has three levels [52]:

1. Level 1 - Perception of the elements in the environment: The first step in achieving SA is to perceive the status and dynamics of the relevant information in the environment. To support this level, the information needs to be displayed in a way that allows successful and effective gathering of information from different sources.
2. Level 2 - This level includes being aware of the elements that are present and their significance considering the operator's goals or system variables. It usually involves making a judgment on the current situation in reference to experienced scenarios. Level 2 SA forms the "so what?" based on Level 1 data that was perceived.
3. Level 3 - Projection of future status: Level 3 SA is concerned with what is going to happen in the near future based on the current state and dynamics of elements. This level is important to allow pilots to be proactive rather than reactive. It represents the "now what?".

4.5.1.1 Situational Awareness Global Assessment Technique (SAGAT)

There are many ways to measure SA, such as subjective ratings, physiological measures, performance criteria, talk-aloud protocol, etc. [50]. In our case, an important selection criterion for the SA measure is its ability to identify which SA level the pilot has reached and understand the problem-solving strategies during taxi navigation. In our research, we used the Situation Awareness Global Assessment Technique (SAGAT), which is a direct objective assessment of the individual's SA. SAGAT is a widely tested and validated objective metric that has been shown to be effective across a variety of domains [53].

To use SAGAT, researchers must conduct a human-in-the-loop simulation and employ “freeze probe”. It means that at several intervals during the experiment, the simulation is paused, and the displays blanked. The participants were not previously aware of the timing of the freeze. Then, participants undergo a series of queries developed to cover all levels of SA i.e., perception, comprehension, and projection (see Annex D: SAGAT questionnaire). Participants answered using an online form or by paper and pencil. The participant's answers are compared to the state of the world at the time of the freeze, offering an objective measure of the participant's SA. After the participants completed the probing, the simulation is resumed from the exact moment it was stopped [54]. In this study, we used 10 SAGAT probes administered during the middle of each scenario.

4.5.2 Workload

Mental workload is a construct representing the cognitive cost incurred by a human to achieve a particular level of performance. It is defined as the difference between the processing capacities required to perform a task and the capacity available at a given moment [55]. Essentially, it reflects the demands imposed by tasks on the limited information-processing capacity of the brain. A useful metaphor is physical workload, where activating the muscles of the body requires energy [56]. Mental workload increases with the addition of tasks (i.e., multitasking) or with higher difficulty or complexity of a single task, potentially leading to workload overload when task demands exceed the operator's processing capabilities [51]. In this research, we evaluated participants' mental workload and performance under different experimental conditions to examine how they managed

taxi clearances provided via the controller. The measure we used was the NASA Task Load Index (TLX) questionnaire.

4.5.2.1 NASA-TLX

NASA TLX is a well-established subjective measure questionnaire that gathers input from the participant. Subjective measures are widely used techniques for workload assessment where subjects are asked to report their experience of workload on a multidimensional scale [57]. NASA TLX rates workload across six dimensions: mental demand, physical demand, time demand, performance, effort, and frustration level [58]. It is the mostly widely used and validated subjective measure of workload [59]. NASA TLX determines the workload of a participant while or immediately after performing a task and provides an overall workload rating [60]. We administered the TLX rating questionnaire, which consists of 20-point Likert-scale items with two anchors at either end, for each of the six dimensions (see Annex C: NASA TLX). The overall workload is the averaged rating over all six dimensions. Note that participants did not weight the importance of each dimension i.e., TLX ranking questionnaire. Hence the workload score reported in this study is the raw, or unweighted, TLX.

4.5.3 Usability

The usability test for this study focused on evaluating the user experience and effectiveness of the integrated CPDLC system with the AMM during taxi operations. The usability assessment involved pilots interacting with the system in both time-critical and non-critical scenarios to determine its ease of use, efficiency, and overall user satisfaction. We measured usability for the CPDLC-AMM application, but not of the baseline condition as it does not involve any interactive system.

We employed the System Usability Scale (SUS) and the User Experience Questionnaire (UEQ) to gather quantitative and qualitative data on the system's usability. Participants rated the system on factors such as ease of navigation, clarity of information, and the intuitiveness of the interface. Additionally, their feedback on the system's learnability, the perceived workload, and the effectiveness of the AMM in enhancing SA was collected. The results from these tests helped identify any usability issues and provide insights for further refinement of the system to ensure it meets the operational needs of pilots in diverse conditions.

4.5.3.1 System Usability Scale (SUS)

The SUS consists of ten five-point Likert-scale items anchored at either end with disagree or agree (see Annex E: SUS Questionnaire). The questions address how learnable and how usable a system is. The answers result in a system usability score represented by scores between 0 and 100, with 0 for the least and 100 for the best perceived usability [61].

4.5.3.2 User Experience Questionnaire (UEQ)

The UEQ questionnaire is used to measure the user experience of interactive systems and gives insights into more complex aspects of user experience [62]. Respondents are presented with a set of words that represent opposite ends of a scale and are asked to rate their experience with the device on a seven-step scale between these word pairs (see Table 4.1). In this study, we selected 11 bipolar adjective pairs that participants rated on a 7-point scale (where 1 = most favorable and 7 = least favorable, see Annex F: UEQ).

Table 4.1 UEQ Item Pairs

Evaluated Items (Opposing Adjectives)
Efficient – Inefficient
Predictable – Unpredictable
Secure – Not Secure
Clear – Confusing
Supportive – Obstructive
Easy – Complicated
Motivating – Demotivating
Attractive – Unattractive
Pleasant – Unpleasant
Innovative – Conservative

4.5.4 Navigational Errors

We assessed navigational accuracy by identifying whether pilots followed the taxi clearances correctly during each scenario. A screen recording of the CPDLC-AMM interface was captured

using SimpleScreenRecorder³ (open-source software), which included the AMM display showing the aircraft's position and the assigned taxi route.

Navigational errors were defined as deviations from the cleared taxi route, such as missed turns, incorrect taxiway entries, or failure to follow a rerouted path. These errors were detected by visually comparing the aircraft's path on the AMM to the expected trajectory based on the clearance displayed.

All recordings were saved as mp4 files and reviewed manually by the researcher to identify instances of route deviation. This method allowed for precise evaluation of pilot adherence to taxi instructions and provided a clear basis for quantifying navigational accuracy.

4.6 Procedure

Prior to commencing the simulator experiment, each participant was welcomed and briefed on the purpose of the study, the experimental setup, and the functionalities of the CPDLC-AMM interface. Participants were given a brief walkthrough of the interface elements and were allowed a short familiarization session in the simulator to reduce any learning bias. Once they were comfortable, the actual experiment began.

Each participant completed six taxiing scenarios under two different communication conditions: (1) traditional radio-based communication and (2) CPDLC-AMM integrated communication. The six scenarios were divided into three functional groups, as discussed above, reflecting real-world operational contexts at busy airports. To ensure counterbalancing and minimize bias, the order of communication mode and scenario assignment was systematically rotated across participants. This approach ensured that every scenario was tested under both conditions across participants, maintaining consistent task complexity and eliminating order effects.

During each scenario, participants received taxi instructions either via radio or through the CPDLC-AMM interface. In CPDLC trials, instructions were visually presented and color-coded on the AMM, and participants responded using predefined acknowledgment buttons (e.g., WILCO, UNABLE). In radio trials, instructions were delivered verbally by the researcher acting as ATC,

³ SimpleScreenRecorder: <https://simplescreenrecorder.com/>

with participants responding verbally. Importantly, during radio communication trials, participants were provided with printed Jeppesen taxi charts for KLAX (see Annex G: Jeppesen taxi charts) and the current Automatic Terminal Information Service (ATIS) (see Annex H: ATIS), to simulate realistic operational conditions. This ensured parity with industry-standard procedures used in traditional voice-based environments. The simulation was paused once in the middle of each scenario for SAGAT probing to objectively assess SA without prior notice to participants.

After each scenario, participants completed a questionnaire measuring workload (NASA-TLX). Additionally, screen recordings were used to capture interaction accuracy and navigation performance throughout the trials. Upon completing all six scenarios, participants also completed usability (SUS and UEQ) questionnaires, along with debriefing, and were invited to provide open-ended feedback on their experience with both systems.

4.7 Data Analysis Plan

To comprehensively evaluate the impact of the CPDLC-AMM system on pilot performance and user experience, a multi-dimensional data analysis strategy was employed. This plan integrated both quantitative and qualitative methods to assess cognitive workload, SA, usability, communication accuracy, and navigation performance across different experimental conditions.

Quantitative analysis was conducted using descriptive statistics (means, standard deviations) followed by inferential tests to compare outcomes between the experimental (CPDLC-AMM) and baseline (radio) conditions. For subjective workload, NASA-TLX scores were computed across all six scenarios per participant and analyzed using paired-samples t-tests. Where the assumption of normality was violated (as confirmed by the Shapiro-Wilk test), non-parametric equivalents such as the Wilcoxon signed-rank test were used. Effect sizes (η^2) were reported alongside p-values to indicate the practical significance of any differences observed.

SA was assessed through the SAGAT method. Participants' responses during the freeze probes were scored as either correct (100%) or incorrect (0%) compared to the current situation in the flight simulator when the freeze occurred. Scores for questions related to SA level 1 were averaged together to offer the measure of SA level 1, and similarly for questions related to SA level 2 and 3. The averaged scores of all questions was the measure of Global SA. Measures of SA level 1, 2, 3

and Global SA were then compared between the two conditions using parametric or non-parametric tests based on distribution characteristics. Statistical validation ensured both accuracy and reliability in identifying differences in SA between communication modes.

Objective performance metrics included navigation errors (e.g., wrong turns, missed instructions), extracted from video recordings of the simulator trials. These measures enabled an assessment of communication clarity and operational reliability under both nominal and non-nominal taxi scenarios.

Usability and user experience were evaluated using two standardized instruments: the System Usability Scale (SUS) and the User Experience Questionnaire (UEQ). Total and subscale scores were calculated for each participant, and descriptive statistics were reported. Item-level analysis identified specific interface attributes that were rated positively (e.g., ease of use, clarity) or flagged for improvement (e.g., reliability, integration). Correlation analyses were also conducted to explore relationships among usability, workload, and SA scores, highlighting any systemic interactions between cognitive demand and user satisfaction.

Taken together, this multi-method analysis framework allowed for a robust and holistic evaluation of the CPDLC-AMM system's effect on human performance. It ensured the validity of conclusions drawn from both objective system data and subjective user feedback, thus supporting a meaningful comparison with conventional radio-based communication in the context of airport surface operations.

4.8 Ethical Considerations

This study was conducted in strict accordance with ethical guidelines governing research involving human participants. Prior to the commencement of data collection, the study protocol, including recruitment methods, data handling procedures, and consent forms, was reviewed and approved by the Polytechnique Montréal Research Ethics Committee under the certificate number CER-2425-27-D (see Appendix A). All participants signed an informed consent form before the experiment, see Appendix I.

CHAPTER 5 RESULTS AND DISCUSSION

Building on the methodology described in the previous chapter, this section presents the experimental findings that evaluate the effectiveness of the CPDLC-AMM prototype. The results provide quantitative and qualitative insights into the system's impact on pilot performance across both nominal and time-critical ground operations.

5.1 Situational Awareness

Figure 5.1 presents the results for SA Overall, participants demonstrated consistently higher SA under the CPDLC-AMM condition across all three levels. Variability was reduced for Level 2 (Comprehension), where scores clustered more tightly under CPDLC-AMM compared to radio. At Level 3 (Projection), however, an outlier was observed under CPDLC-AMM, with one participant scoring near zero, which widened the range of scores. Even so, the group mean at this level remained higher for CPDLC-AMM than for radio, indicating that the system generally supported more accurate projection despite greater individual variability.

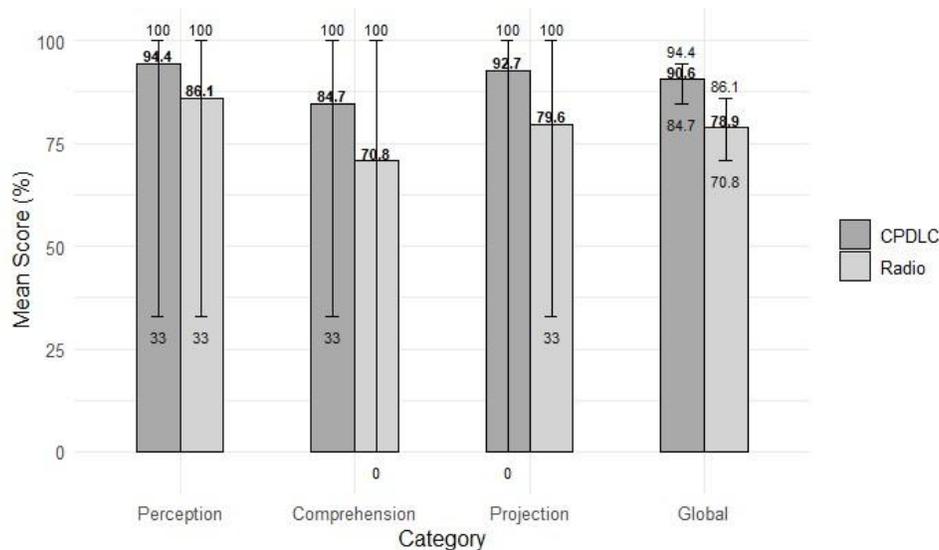


Figure 5.1 Situational awareness scores by levels and format

A statistical analysis further supports these results. Participants demonstrated significantly higher overall SA when using CPDLC-AMM ($M = 90.6\%$) compared to traditional radio communication ($M = 78.9\%$). This difference was statistically significant, $t(7) = 2.51$, $p = .016$, with a moderate-

to-large effect size, $\eta^2 = 0.12$, indicating that 12% of the variance in SAGAT scores was attributable to communication format. Due to violations of normality assumptions (Shapiro–Wilk $p < .05$), these results were further validated using a non-parametric Mann–Whitney U test, which also confirmed significance ($U = 408.5$, $p < .05$).

Further analysis at the three hierarchical levels of SAGAT revealed statistical significance with higher levels of SA. For Level 1 (Perception), the effect was strong, $t(7) = 2.30$; for Level 2 (Comprehension), the difference approached significance, $t(7) = 1.57$, with CPDLC-AMM showing both higher mean and reduced variability; and for Level 3 (Projection), the difference was statistically significant, $t(7) = 1.73$, though accompanied by higher variability due to the low-scoring outlier. These results suggest that the CPDLC-AMM system particularly enhanced participants' perception and projection of the situation, while providing more consistent comprehension across participants.

5.1.1 Impact of Scenario Criticality on Situational Awareness

To explore how scenario complexity influences global SA, global scores were analyzed across the three groups discussed in the previous chapter under both communication formats. The results are presented in Figure 5.2.

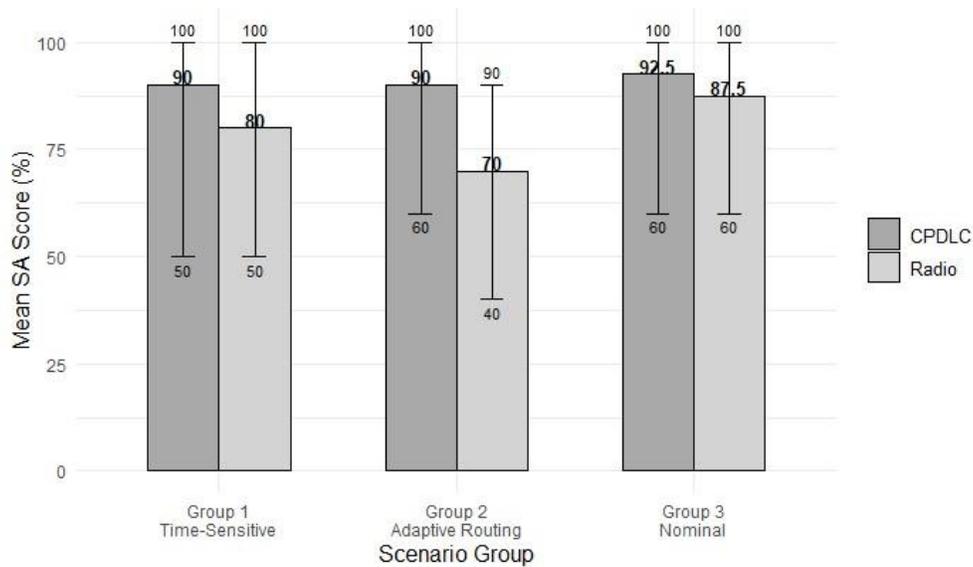


Figure 5.2 Global situational awareness by scenario type and format

To test the combined effects of communication format and group assignment on performance, a 3 (Group: 1, 2 and 3) \times 2 (Format: CPDLC vs. Radio) repeated-measures ANOVA was conducted. The analysis revealed a significant main effect of Group, $F(2, 14) = 5.42$, $p = .018$, $\eta^2 = .070$, indicating that average performance scores differed across the three experimental groups. The main effect of Format was not statistically significant, $F(1, 7) = 4.40$, $p = .074$, $\eta^2 = .132$, suggesting that communication format alone did not produce a reliable difference in performance. The interaction between Group and Format approached significance, $F(2, 14) = 3.63$, $p = .054$, $\eta^2 = .042$, indicating a trend that the effect of communication format may have varied across groups, though this did not reach the conventional level of significance. Mauchly's test confirmed that the assumption of sphericity was met for both the Group factor ($W = .72$, $p = .375$) and the Group \times Format interaction ($W = .98$, $p = .951$); therefore, no corrections were applied.

Nevertheless, a closer inspection of the descriptive results revealed differing patterns. Participants using CPDLC-AMM maintained high SA levels in both conditions, with only a 2.5% drop between nominal and non-nominal scenarios. In contrast, performance with radio dropped sharply (-12.5%) in non-nominal conditions, suggesting reduced cognitive resilience under complexity.

These findings highlight the operational robustness of the CPDLC-AMM system. By sustaining higher levels of SA even during time-critical or unexpected events, the system demonstrates a

distinct advantage over radio communication, particularly in complex surface environments where rapid route updates or conflict resolutions are essential.

5.2 Workload

To evaluate the effect of communication format and scenario complexity on pilot workload, data were collected using the NASA Task Load Index (NASA-TLX). This multidimensional tool assesses six subcomponents of perceived workload: mental demand, physical demand, temporal demand, performance, effort, and frustration, each rated from 1 (low) to 10 (high). An overall workload score was computed for each trial by averaging these six dimensions.

Table 5.1 Results of 3×2 repeated measures ANOVA on workload.

Effect	F(df)	p-value	Interpretation
Communication Format	F(1,7) = 7.04	0.033	Statistically significant main effect
Scenario Group	F(2,14) = 1.62	0.233	Not statistically significant
Format × Group Interaction	F(2,14) = 0.096	0.909	Not statistically significant

As shown in Figure 5.3, pilots reported significantly lower cognitive workload when using the CPDLC-AMM system ($M = 1.99$ out of 10) compared to baseline radio communication ($M = 3.03$), with particularly notable reductions in mental demand and frustration scores. This difference was statistically significant, $t(23) = -4.04$, $p < .001$, with a large effect size, $\eta^2 = 0.415$. A Shapiro-Wilk test confirmed the normality of workload scores in both groups, validating the use of parametric tests. Additionally, variance in workload was substantially lower under CPDLC-AMM, indicating a more consistent user experience across taxi scenarios.

These findings also shows that CPDLC-AMM consistently yielded lower workload ratings across all three scenario groups: time-sensitive, adaptive routing, and nominal. Furthermore, nominal scenarios were rated as less demanding than non-nominal ones regardless of communication mode, suggesting that both system design and operational complexity influence perceived workload.

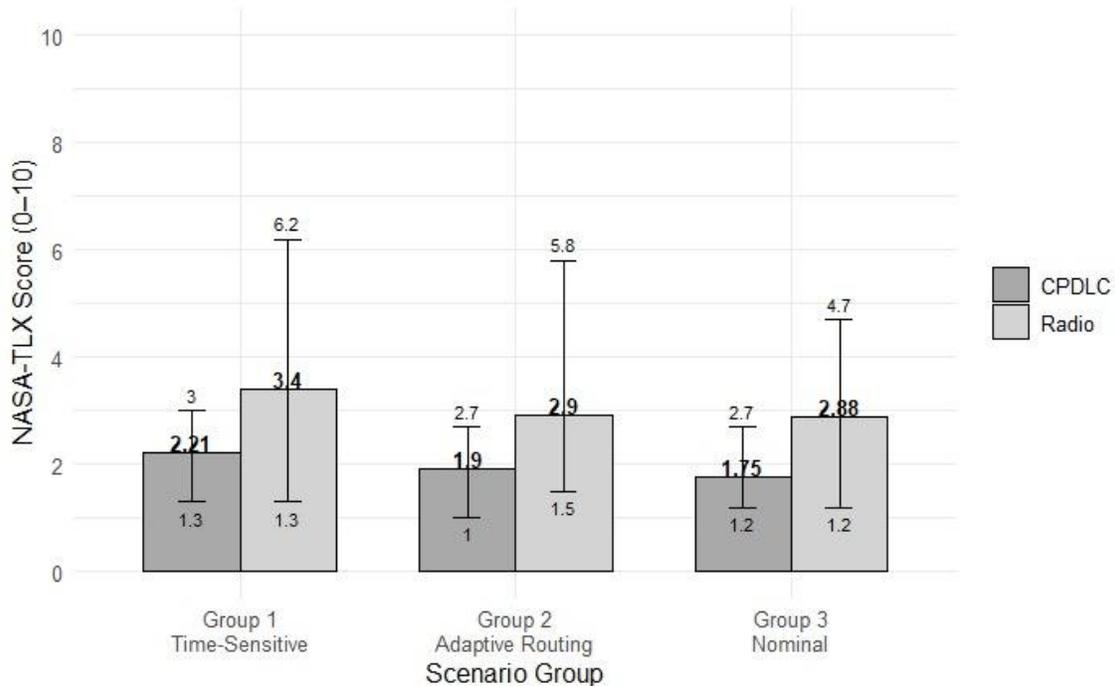


Figure 5.3 Overall NASA-TLX workload scores across scenario types and communication formats.

To statistically validate these effects, a 3×2 repeated-measures ANOVA was conducted with Group (1, 2, and 3) and Communication Format (CPDLC vs. Radio) as within-subjects factors. The results, as summarized in Table 5.1, revealed a significant main effect of Communication Format, $F(1, 7) = 7.04$, $p = .033$, $\eta^2 = .502$, indicating that workload ratings differed significantly between CPDLC and Radio formats. The main effect of Group was not statistically significant, $F(2, 14) = 1.62$, $p = .233$, $\eta^2 = .188$, suggesting that average workload ratings did not vary reliably across the three scenario groups. The interaction between Group and Format was also not significant, $F(2, 14) = 0.096$, $p = .909$, $\eta^2 = .014$, indicating that the effect of communication format on workload was consistent across scenario groups. Since the Format factor has only two levels, the assumption of sphericity is inherently satisfied. For the Group and Group \times Format effects, no corrections were applied due to the absence of evidence suggesting a violation of sphericity.

5.2.1 Dimension-Level Insights

To further explore the specific components of workload influenced by the communication format, individual NASA-TLX subscales were analysed (Figure 5.4). Across all six dimensions, CPDLC-

AMM produced lower median scores than radio communication, reflecting lower perceived workload.

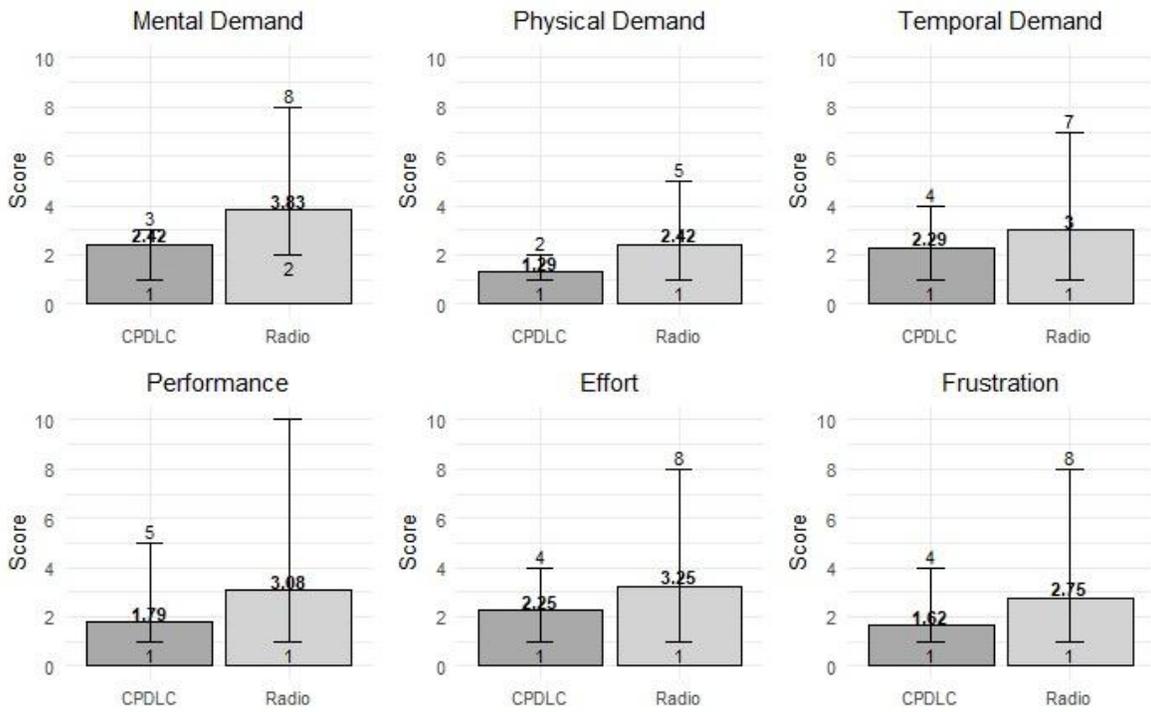


Figure 5.4 Distribution of NASA-TLX subscale scores by communication format.

The greatest reductions were observed in physical demand, frustration, and performance burden, with CPDLC-AMM scores clustering tightly around 1–2, indicating minimal strain in these areas. Notably, in NASA-TLX, a lower performance score indicates better self-perceived performance, and lower values on effort and frustration reflect more favourable experiences.

These results suggest that the CPDLC-AMM system not only reduces the overall cognitive burden but also mitigates the physical and emotional strain associated with traditional radio communication. This supports its suitability for both nominal operations and non-nominal, high-workload scenarios.

5.3 Usability

To evaluate the usability of the CPDLC-AMM system in both nominal and non-nominal contexts, participants completed the System Usability Scale (SUS) and a customized version of the User Experience Questionnaire (UEQ) at the end of their sessions.

5.3.1 SUS

The SUS, composed of 10 items alternating between positive and negative formulations on a 5-point Likert scale, provides a global usability score out of 100. The system received a mean SUS score of 68.12, which aligns with the standard benchmark for “acceptable” usability [63]. While not indicating exceptional usability, this score positions the CPDLC-AMM system above the threshold for usability acceptability and suggests a generally positive user experience.

Participant scores ranged from 57.5 to 80, with a standard deviation of 9.23 and a median of 68.75. The resulting bimodal distribution (see Figure 5.5) suggests the existence of two distinct groups in terms of perceived usability. Group 1, composed of older and more experienced aviation professionals, tended to rate the system more critically. In contrast, Group 2, comprised of younger and less experienced users who were more familiar with modern technologies such as CPDLC, evaluated the system more positively. This variation highlights how factors such as age, professional background, and technological familiarity influence user perceptions and acceptance of new systems.

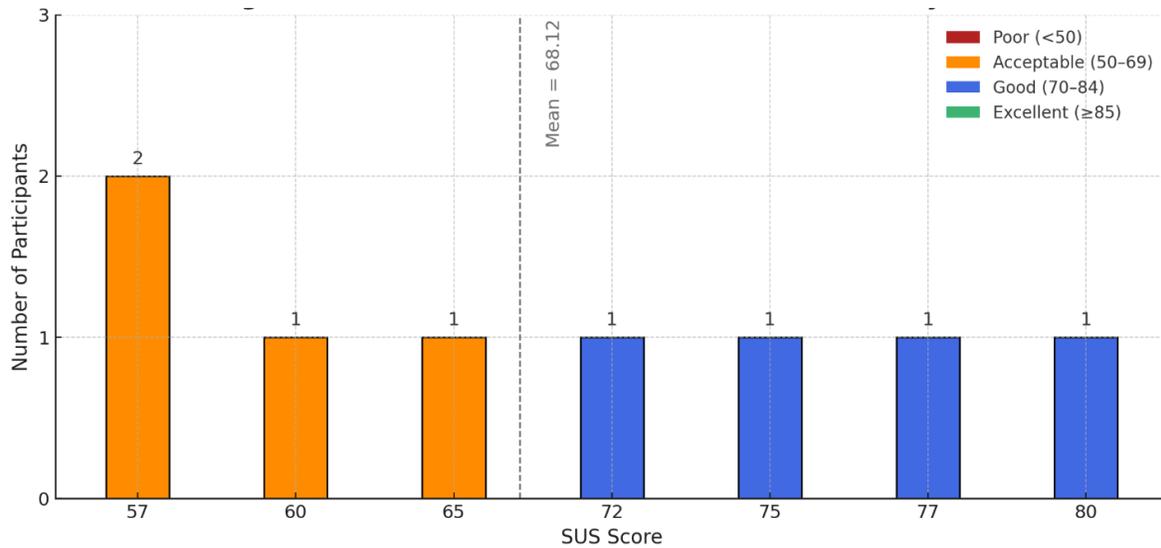


Figure 5.5 Overall SUS score

Item-level analysis (Figure 5.6) further revealed that users particularly appreciated the system's ease of learning, user confidence, and low need for technical support, as reflected by high ratings on items frequency of use, learning, confidence and learning requirement. However, the integration of system functions (item 5) was identified as an area requiring improvement, as it received lower and more dispersed scores. Negative-formulated items (complexity, support, inconsistency, cumbersome) were generally rated favourably, indicating that issues such as inconsistency, complexity, and the burden of use were not perceived as major concerns by most participants.

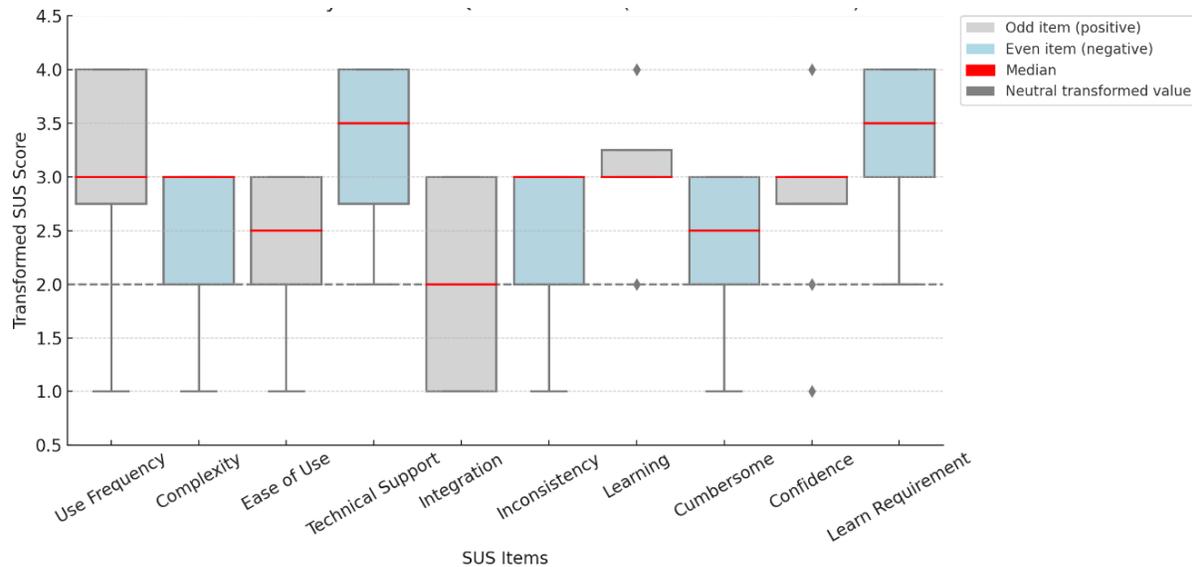


Figure 5.6 Item-level analysis of SUS questionnaire

5.3.2 UEQ

The user experience of the CPDLC-AMM system was assessed using 11 opposing adjective pairs rated on a 7-point semantic differential scale. As shown in Figure 5.7, most items received mean scores below the neutral midpoint of 4, indicating a generally favorable perception of the system across participants.

The most positively rated items were:

- Motivating–Demotivating and Innovative–Conservative (both $M = 2.5$),
- followed by Practical–Impractical ($M = 2.6$),
- Clear–Confusing and Predictable–Unpredictable (each $M = 2.8$).

These results suggest that participants found the system engaging, novel, and functionally clear.

Several items were rated moderately positive, including Pleasant–Unpleasant, Easy–Complicated, Supportive–Obstructive, and Efficient–Inefficient (all $M = 2.9$), indicating that users generally found the system usable and supportive during operation.

A more neutral score was seen for Attractive–Unattractive ($M = 3.2$), reflecting mixed opinions about the system’s aesthetic appeal. The least favorable item was Secure–Not Secure ($M = 4.2$),

pointing to concerns about the system's perceived reliability or safety. This suggests that while the interface was found useful and motivating, there may be a need to improve user trust and assurance regarding system integrity.

Overall, the results indicate a positive user experience, particularly in terms of motivation, innovation, and clarity. However, perceptions of security and visual attractiveness varied across participants and may benefit from targeted refinements.

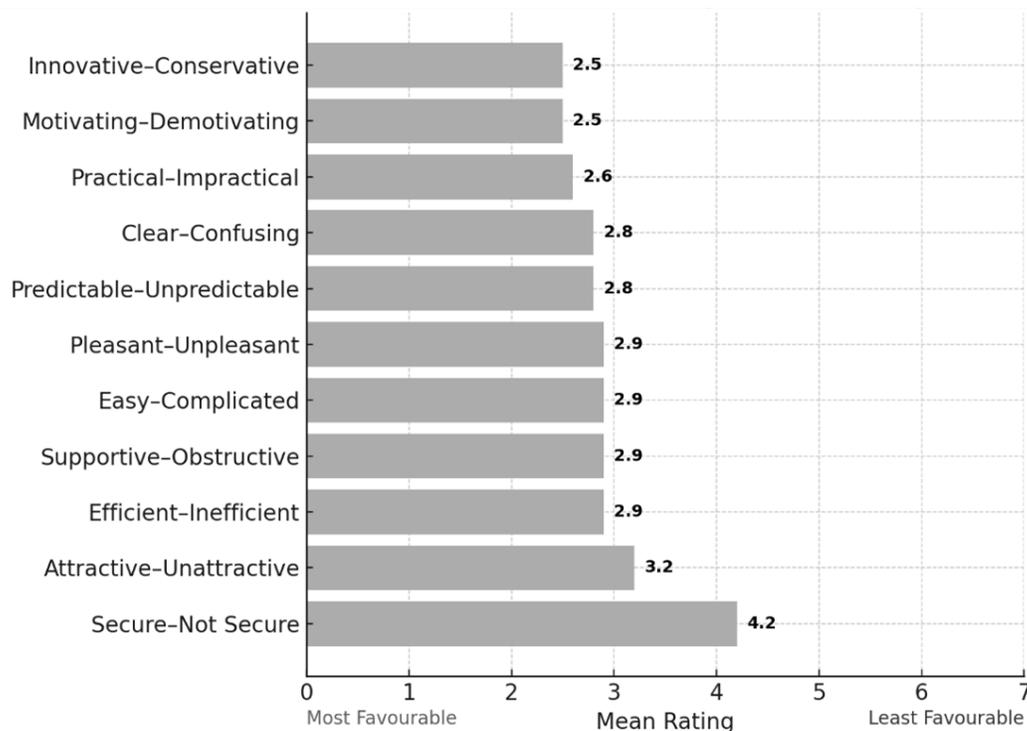


Figure 5.7 Item-level UEQ score

5.4 Navigational Errors

To evaluate performance accuracy, observed navigation errors were analyzed across the 48 experimental trials (8 participants, each completing 6 scenarios). The majority of navigation errors stemmed from incorrect turns either premature or delayed while attempting to enter the designated taxiway. Overall, 9 navigation errors were recorded, corresponding to a global error rate of 18.75%.

A clear disparity emerged between the two communication formats. Radio communication accounted for all 9 observed errors, yielding a 37.5% error rate (9 errors out of 24 trials). In contrast, the CPDLC-AMM system achieved flawless performance, with zero navigation errors across its 24 trials, representing a 100% success rate.

At the individual level, four participants made one navigation error each, while two participants committed multiple errors. All of these occurred exclusively during radio trials. Notably, the same participants made no errors under the CPDLC-AMM condition, reinforcing the assumption that the system positively influenced task execution.

Scenario-wise, the most error-prone situations were S1 and S6, both under the radio condition. Scenario 1 (S1), a non-nominal and time-critical scenario, saw three navigation errors. Scenario 6 (S6), though nominal, generated two errors, likely due to the complexity of its taxi routes. Importantly, the counterbalancing of scenarios ensures that these discrepancies are not due to scenario order or learning effects.

Additionally, two communication-related issues contributed to navigation errors in the radio condition: one pilot misinterpreted a controller clearance, and another instance involved intra-crew misunderstanding, causing confusion during taxi. Conversely, although some users reported interface handling difficulties with CPDLC-AMM (e.g., button misuse), these did not result in any operational errors.

Collectively, these findings suggest that the structured, visual, and standardized nature of CPDLC-AMM enhances operational reliability by minimizing interpretation errors and improving situational clarity. The system demonstrably reduced both navigation and communication-related errors compared to traditional radio, supporting its usability and functional robustness during ground operations.

5.5 Discussion

This study demonstrates that the CPDLC-AMM system provides substantial operational and cognitive benefits over traditional radio communication during taxi operations. The central

research question, whether an integrated CPDLC-AMM system can match or outperform voice communication, particularly in non-nominal, time-critical scenarios, can be answered positively. Across all metrics, CPDLC-AMM showed either non-inferiority or clear superiority.

Workload (H1, H4). As predicted by H1, NASA-TLX scores confirmed significantly lower cognitive workload under CPDLC-AMM, particularly for mental demand, frustration, and perceived performance burden. This effect was consistent across nominal and non-nominal scenarios, with the largest reductions observed in time-critical situations, supporting H4 that workload benefits are amplified under higher operational stress. The streamlined interface, predefined response buttons, and synchronized AMM feedback likely contributed to these reductions.

Situational awareness (H2). Supporting H2, participants achieved higher SAGAT scores across all levels of SA—perception, comprehension, and projection—as well as in overall global SA. Variability was reduced for comprehension, while a low-scoring outlier at projection widened the range, though mean scores remained higher under CPDLC-AMM than radio. In non-nominal scenarios, SA dropped sharply with radio (−12.5%) but remained stable with CPDLC-AMM (−2.5%), highlighting the system’s role in maintaining cognitive resilience under complexity. These results align with prior studies such as the EMMA project [22] and work by Stroosma and Hoogeboom [41], which showed datalink-AMM benefits in low-stress settings. This study extends those findings by demonstrating reliability in dynamic, time-sensitive taxi situations, enabled by interface innovations including yellow highlights for outdated routes and pop-up rerouting alerts.

Communication errors (H3). H3 was also supported. No navigation errors occurred with CPDLC-AMM, whereas nine errors were recorded during radio trials, all due to miscommunication or clearance confusion. Structured digital messaging and synchronized AMM feedback reduced ambiguity and prevented errors, illustrating how the system enhances operational safety.

Task efficiency (H4). Pilots using CPDLC-AMM responded more quickly to updated clearances, particularly during rerouting events. This demonstrates that task performance benefits are not limited to error reduction but extend to operational efficiency, with the interface directly supporting faster detection and adaptation to changing conditions.

Usability and user experience (H5). Pilot evaluations confirmed that CPDLC-AMM meets usability and user experience expectations. The mean SUS score of 68.12 reached the threshold for acceptable usability, with higher ratings among younger, tech-savvy participants. UEQ ratings were positive for stimulation, clarity, and efficiency, though some participants noted concerns regarding predictability and system trust. Qualitative feedback emphasized the value of real-time synchronization between CPDLC messages and AMM visuals, particularly at busy airports like KLAX.

Taken together, these findings confirm that CPDLC-AMM reduces workload, enhances situational awareness, minimizes communication errors, improves efficiency, and provides acceptable usability and user experience. By supporting H1 through H5, the study answers the research question affirmatively and positions CPDLC-AMM as a viable, and in some respects superior, alternative to traditional voice communication for surface operations, especially under time-critical and dynamically changing taxi scenarios.

5.6 Implications for design

The findings of this study highlight several implications for future avionics systems supporting taxi operations. A key strength of the CPDLC-AMM system was its ability to handle non-nominal events entirely through the interface, without requiring fallback to radio. The combination of real-time clearance delivery, yellow highlight for outdated routes, and pop-up alerts enabled pilots to quickly detect and adapt to route changes, maintaining high SA even under time pressure.

Contrary to concerns in previous studies about CPDLC delays, the system implemented here ensured instant clearance transmission, and pilots reacted promptly due to the intuitive interface and synchronized AMM visualization. This demonstrates that, with proper design, datalink can support time-critical ground operations as effectively as radio.

These results underscore the importance of integrating visual route confirmation, timely feedback, and message-map consistency in future CPDLC-AMM implementations. Ensuring low-latency ATC communication links and minimizing input burden will be essential to achieve operational readiness and certification in real-world environments.

5.7 Limitations of the study

Several methodological limitations should be acknowledged to contextualize the scope of this study. First, although the use of a flight simulator is suitable for exploratory research, it may influence participant behaviour. Some pilots might have adjusted their vigilance or perceived workload, knowing that the simulation posed no real operational risk. Additionally, individual preferences may have emerged prior to the experiment, particularly among more experienced pilots, some of whom expressed a strong attachment to radio communication. This may have affected their subjective evaluation of the CPDLC-AMM system.

While the protocol included a counterbalanced scenario distribution across both communication formats to limit order effects, repeated exposure to similar scenarios may have induced learning or habituation effects, potentially reducing differences between conditions. From an ergonomic standpoint, the CPDLC-AMM system was displayed on a touch-enabled external monitor mounted within the simulator but not integrated into the primary flight deck. Although functionally coherent, this configuration does not replicate the physical integration of systems in an actual cockpit environment.

Moreover, several logistical and resource-related constraints impacted the study design. Recruiting professional pilots proved challenging due to limited availability, thus restricting the sample size. The AMM and CPDLC systems tested in the experiment were prototype versions developed specifically for this research, rather than certified or commercially available systems. CPDLC messages from ATC were pre-programmed, making faster communication time than if the ATC had to type manually the message. Finally, the ground controller role was enacted by the experimenter, which could not fully reproduce the dynamic nature and pace of real-world ATC communications.

Despite these limitations, methodological robustness was maintained through careful control of variables, iterative design of experimental tools, and collaboration with industry partners. These measures ensured the study remained well-aligned with its research objectives.

CHAPTER 6 CONCLUSION

This study was motivated by a clear and well-documented observation: in the face of ever-increasing air traffic, traditional radio communications alone will soon be insufficient to meet the safety, and efficiency demands of airport ground operations. This challenge, extensively discussed in the literature, provided the foundation for our research.

In response, the integration of CPDLC with AMM was explored as a promising technological solution. While the individual benefits of CPDLC and AMM systems have been demonstrated in previous studies, limited research has examined their combined effectiveness, especially under non-nominal, time-pressured, or cognitively demanding taxi scenarios.

This thesis aimed to address that gap through a human-in-the-loop experimental study evaluating the operational potential of the integrated CPDLC-AMM system. The results confirm the benefits of such integration: across both routine and time-critical taxiing conditions, the system demonstrated a consistent positive effect on perceived workload reduction, pilot performance, and SA.

These improvements are particularly significant in non-nominal contexts, where decision-making must occur under pressure, an area previously underexplored in the literature. The findings also revealed valuable insights into system usability. While participants found the interface largely intuitive, they also identified opportunities for improvement, especially regarding the incorporation of new functionalities.

Taken together, the results suggest that the CPDLC-AMM system holds strong potential for operational deployment. To move toward large-scale implementation, the next critical step will involve embedding the system within onboard avionics and evaluating it in real-world operational conditions. This will help ensure its technical maturity, usability, and effectiveness in live airport environments.

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APPENDIX A ETHICS

CER-2425-27-D



Montréal, le 28 novembre 2024

Objet: Approbation éthique – « Piloting the future: Design of a Data Link system with Airport Moving Map for Taxi » - Projet CER-2425-27-D

Mme Srishti Rawal,

J'ai le plaisir de vous informer que le Comité d'éthique de la recherche, selon les procédures en vigueur, en vertu des documents qui lui ont été fournis, a examiné le projet de recherche susmentionné et conclu que ce dernier répond aux normes en vigueur au chapitre de l'éthique de la recherche énoncées dans la *Politique en matière d'éthique de la recherche avec des êtres humains* de Polytechnique Montréal.

Veillez noter que le présent certificat est valable pour une durée d'un an, soit du 28 novembre 2024 au 27 novembre 2025, pour le projet tel qu'approuvé au Comité d'éthique de la recherche avec des êtres humains.

Veillez noter que conformément aux exigences auxquelles l'institution et son personnel sont assujettis afin d'être admissibles aux fonds des organismes subventionnaires, il est de votre responsabilité de déposer au CÉR un rapport annuel ou un rapport final avant l'expiration de la présente approbation éthique afin de l'informer de l'avancement de vos travaux. Le formulaire à remplir est disponible à l'adresse suivante : (<http://www.polymtl.ca/recherche/formulaires-et-guides>).

De plus, il est de votre responsabilité d'informer le CER de toute modification importante qui pourrait être apportée au protocole expérimental avant sa mise en œuvre, de même que de tout élément ou événement imprévu pouvant avoir une incidence sur le bien-être ou l'intégrité des participant(e)s impliqué(e)s dans le projet de recherche. Nous vous invitons aussi à nous signaler tout problème susceptible d'avoir une incidence sur les membres de l'équipe de recherche.

Je vous souhaite bonne chance dans la poursuite de vos travaux.

Nous vous prions d'agréer, Madame, l'expression de nos sentiments les meilleurs,

L'Hocine Yahia, vice-président
Comité d'éthique de la recherche
Polytechnique Montréal

c.c. Direction de la formation et de la recherche; Service des Finances
Philippe Doyon-Poulin, Professeur adjoint, Département de mathématiques et de génie industriel
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Cochercheurs
p.j. Certificat # CER-2425-27-D

Comité d'éthique de la recherche
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CER-2425-27-D

**POLYTECHNIQUE
MONTREAL**

 UNIVERSITÉ
D'INGÉNIERIE

CERTIFICAT D'APPROBATION ÉTHIQUE

Le Comité d'éthique de la recherche de Polytechnique Montréal, selon les procédures en vigueur, en vertu des documents qui lui ont été fournis, a examiné le projet de recherche suivant et conclu qu'il respecte les règles d'éthique énoncées dans sa Politique en matière d'éthique de la recherche avec des êtres humains.

Projet	
Titre du projet	Piloting the future: Design of a Data Link system with Airport Moving Map for Taxi CER-2425-27-D
Étudiante requérante	Srishti Rawal , Candidate au doctorat, Département des mathématiques et de génie industriel
Sous la direction de:	Philippe Doyon-Poulin, Professeur adjoint , Département de mathématiques et de génie industriel, Polytechnique Montréal & Guchuan Zhu, professeur titulaire , Département de génie électrique, Polytechnique Montréal.
Avec la collaboration de:	Jeremy Cooperstock (McGill)
Étudiant(e)s couvert(e)s:	Benjamin Berton (PhD - Polymtl), Corentin Conan (McGill)

Financement	
Organisme	CRSNG / CRIAQ
No de UBR	3101581 et 3280215
Programme	
No d'octroi:	
Titre original de l'octroi:	
Chercheur principal:	

MODALITÉS D'APPLICATION

Toute modification importante qui pourrait être apportée au protocole expérimental doit être transmise au Comité avant sa mise en œuvre.

L'équipe de recherche doit informer le Comité de tout élément ou événement imprévu pouvant avoir une incidence sur le bien-être ou l'intégrité des participant(e)s impliqué(e)s dans le projet de recherche ainsi que tout problème susceptible d'avoir une incidence sur les membres de l'équipe de recherche.

Selon les règles universitaires en vigueur, un suivi annuel est minimalement exigé pour maintenir la validité de la présente approbation éthique, et ce, jusqu'à la fin du projet. Le questionnaire de suivi est disponible sur la page web du Comité.

Guillaume Paré, conseiller, DRI, pour L'Hocine Yahia.

 L'Hocine Yahia, vice-président
Comité d'éthique de la recherche
Polytechnique Montréal

 Date de délivrance :
28 novembre 2024

 Date de fin de validité :
1er décembre 2025

 Date du prochain
suivi :
27 novembre 2025

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2500, chemin de Polytechnique
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APPENDIX B BRIEFING QUESTIONNAIRE

1. Participant ID:

2. Age:

3. Gender:
 - Male
 - Female
 - Prefer not to say

4. Education level completed:
 - High School/CEGEP
 - Bachelor
 - Masters
 - PhD

5. Years of experience in aviation
 - 0-5 years
 - 6-10 years
 - 11-15 years
 - 16-20 years
 - 21+ years

6. Flight hours:

7. Airports you are most familiar with:

- 0-5 years
- 6-10 years
- 11-15 years
- 16-20 years
- 21+ years

8. How familiar are you with using datalink communication ex. CPDLC:

- Unfamiliar
- Little familiar ex. Used a few flights
- Somewhat familiar ex. Used on several flights
- Very familiar ex. Used frequently

9. Equipment you are familiar with for taxi:

- Printed airport charts
- Electronic airport charts
- Airport Moving Map
- Electronic Flight Bag (ex. Foreflight or company specific)

APPENDIX D SAGAT QUESTIONNAIRE

Level 1: Perception

1. What is the current position of your aircraft on the taxiway?

Note: Write the exact taxiway name/position of the approximate position or unknown if position is unknown.

2. Are all taxiway signs and markings clearly visible from your current position
 - Yes
 - No
 - Unsure
3. What is the current status of your taxi clearance
 - Clear to taxi
 - Hold short
 - Re-route required
 - Unknown

Level 2: Comprehension

4. What is the significance of the last message received from ATC regarding your taxi clearance?
 - Continue as planned
 - Stop and hold position
 - Change taxi route
 - Unsure
5. Are there any potential conflicts or hazards ahead on your taxi route?
 - Yes
 - No
 - Unsure
6. What is the current operational state of the runway you are approaching (e.g. active, closed, occupied)
 - Active

- Closed
- Occupied
- Unsure

Level 3: Projection

7. What is the likely next instruction you will receive from ATC?
 - Continue taxiing
 - Hold position
 - Line up and wait
 - Takeoff clearance
 - Unsure
8. Given the current traffic situation, how likely is it that you will need to reroute or hold before reaching the runway?
 - Very likely
 - Likely
 - Unlikely
 - Very unlikely
 - Unsure
9. If ATC sends a route change via CPDLC during taxi, what actions will you prioritize to ensure safe compliance with the new clearance?
 - Cross-check the updated route on the AMM to verify position and path
 - Confirm the revised route with ATC if there is any ambiguity
 - Continue on the original path until further clarification.
 - Unsure
10. If you notice a discrepancy between the AMM display and the CPDLC message during taxi, what would be your immediate action?
 - Stop and clarify with ATC
 - Follow AMM
 - Follow CPDLC
 - Wait for further instructions

APPENDIX E SUS QUESTIONNAIRE

Please enter your participant number: _____

System Usability Scale (SUS)

	Strongly Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Strongly Agree
1. I think I would like to use this system frequently.	<input type="checkbox"/>				
2. I found the system unnecessarily complex.	<input type="checkbox"/>				
3. I thought the system was easy to use.	<input type="checkbox"/>				
4. I think that I would need the support of a technical person to be able to use this system.	<input type="checkbox"/>				
5. I found the various functions in this tool were well integrated.	<input type="checkbox"/>				
6. I thought there was too much inconsistency in this tool.	<input type="checkbox"/>				
7. I would imagine that most people would learn to use this system very quickly.	<input type="checkbox"/>				
8. I found the tool very cumbersome to use.	<input type="checkbox"/>				
9. I felt very confident using the system.	<input type="checkbox"/>				
10. I needed to learn a lot of things before I could get going with this system.	<input type="checkbox"/>				

APPENDIX G JEPPESEN MAP FOR KLAX

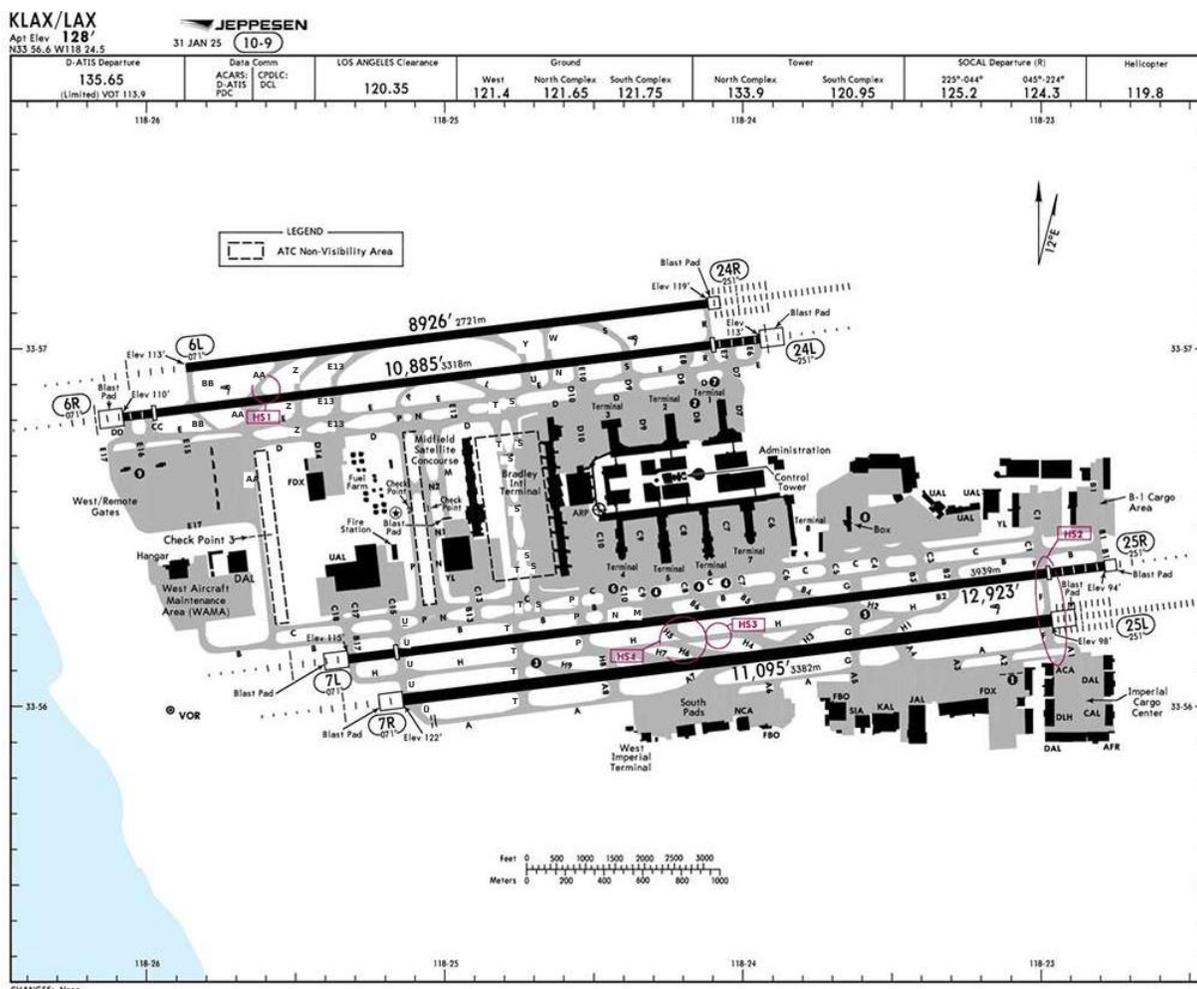


Figure G.1 Printed Jeppesen taxi charts for KLAX used with radio for baseline

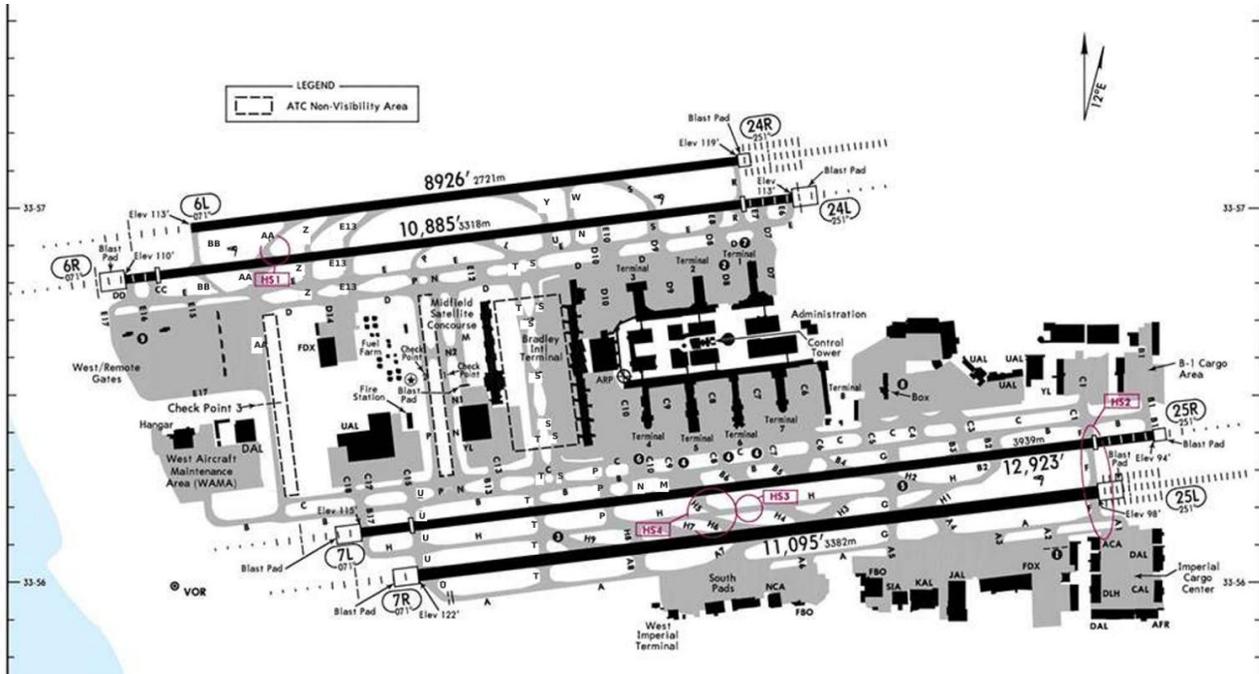


Figure G.2 Zoomed version of printed Jeppesen taxi charts for KLAX

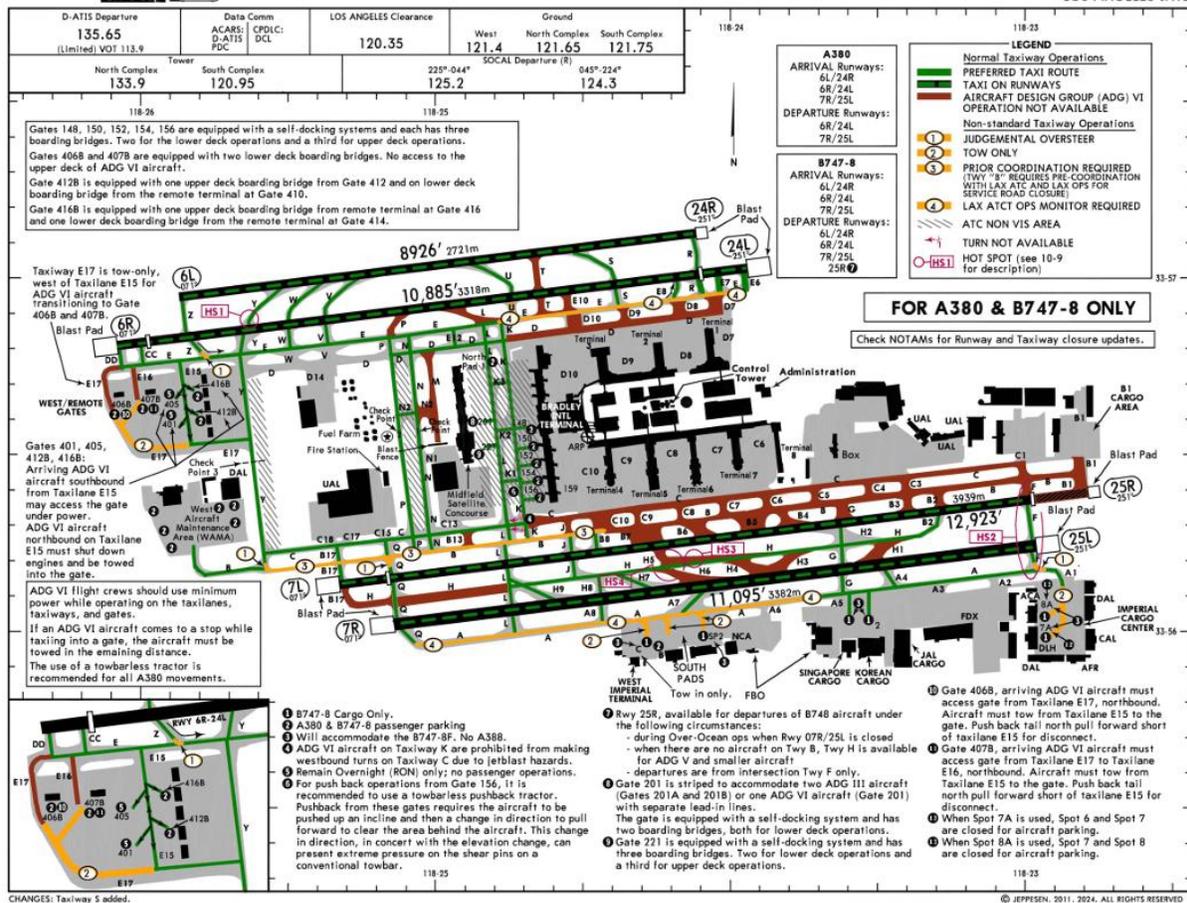


Figure G.3 Printed Jeppesen taxi charts for KLAX (for A380 and B747-8 only)

APPENDIX H ATIS

ATIS PROVIDED TO PILOTS⁴:

LAX ATIS INFO Y 1453Z. 14004KT 8SM FEW017 OVC025 18/12 A3000 (THREE ZERO ZERO ZERO) RMK AO2 SLP157 T01780122 53014. CTC L A GC ON 121.75 FOR PUSH OR TAXI ON A. RY 24R, 25L SFL OTS, SEAL BEACH, VENTURA VOR OTS. HAZD WX INFO FOR LAX AREA AVBL FM FSS. USE CAUTION FOR HANG GLIDING 1 MILE SOUTH LOS ANGELES VOR. BIRD ACTIVITY VICINITY ARPT. INCLUDE YOUR CALL SIGN IN ALL READBACKS. CAUTION. RUNWAY INCURSIONS HAVE OCCURRED AT TAXIWAYS V, W, AND Y NEAR RWY 24L. PILOTS MUST HOLD SHORT WHEN INSTRUCTED AND READBACK ALL HOLD SHORT CLEARANCES. REMAIN ALERT AND EXERCISE EXTREME CAUTION. ...ADVS YOU HAVE INFO Y.

"Los Angeles International Airport, ATIS Information Yankee, time one four five three Zulu. Wind one four zero at zero four. Visibility eight. Few clouds one seven hundred, overcast two thousand five hundred. Temperature one eight, dew point one two. Altimeter three zero zero zero. Remarks: automated observation, sea-level pressure one five seven, temperature one seven point eight, dew point one two point two, pressure falling rapidly."

"Contact Los Angeles Ground Control on one two one point seven five for pushback or taxi on taxiway Alpha."

"Runways two four right and two five left surface flooding lights out of service. Seal Beach and Ventura VORs out of service."

"Hazardous weather information for the LAX area available from Flight Service Station. Use caution for hang gliding activity one mile south of Los Angeles VOR. Bird activity in the vicinity of the airport."

⁴ KLAX ATIS: <https://datis.cloudw.io/klax>

"Include your call sign in all readbacks. Caution: runway incursions have occurred at taxiways Victor, Whiskey, and Yankee near runway two four left. Pilots must hold short when instructed and read back all hold short instructions. Remain alert and exercise extreme caution."

"Advise on initial contact you have Information Yankee."

APPENDIX I INFORMATION AND CONSENT FORM



Information and consent form

Title of research activity:

Piloting the future: Design of a Data Link system with Airport Moving Map for Taxi

Research team:

Research project Supervisor

Srishti Rawal

Student, Polytechnique Montréal – Department of Mathematics and Industrial Engineering

Telephone number: 1-438-365-9334

Email Address: srishti-2.rawal@polymtl.ca

Researchers

Benjamin Berton, PhD student, Polytechnique Montréal

Corentin Conan, PhD student, McGill University

Jeremy Cooperstock, Professor, McGill University

Philippe Doyon-Poulin, Professor, Polytechnique Montreal

Guchuan Zhu, Professor, Polytechnique Montreal

Funding of the research activity:

This research activity is funded as part of a research program up to 40% by the Science and Engineering Research Council of Canada (NSERC, a federal funding agency), 40% by the aviation research Consortium of Québec (CRIAQ, a provincial funding body) and 20% by the following industrial partners: Bombardier, CMC Electronics, Marinvent, Presagis and Thales.

Conflicts of interest

The research team does not have a conflict of interest in terms of the present research project.

Preamble

We invite you to participate in a study focused on exploring the potential of integrating Controller Pilot Data Link Communication (CPDLC) with Airport Moving Maps (AMM) to enhance communication accuracy and situational awareness during taxi navigation in aviation. The purpose of this study is to assess how these systems can improve efficiency and safety during both time-critical and non-critical taxiing scenarios.

To achieve these objectives, we will conduct human-in-the-loop simulations that will allow us to evaluate the system's performance and its impact on pilot workload and communication effectiveness. Your participation will provide valuable insights that could contribute to the development of more advanced and reliable communication tools in aviation.

However, before agreeing to participate in this activity and sign this information and consent form, please take the time to read the information presented.

We invite you to ask all the questions that you deem useful to the person in charge of the research activity or to any other member of the research team and to ask them to explain any word or information that is not clear. We also invite you to seek advice from any other person from whom you would like advice about your possible participation.

General presentation of the research project

The objective of this study is to design and evaluate a data link communication channel with integrated airport moving map for taxi navigation. This system will support the pilots to taxi on the surface in both time-critical and non-critical scenarios.

To achieve these objectives, we will conduct human-in-the-loop simulations that replicate realistic taxiing scenarios. Data will be collected through pilot performance assessments and interviews to gain insights into the effectiveness of the integrated system. The findings from this study will contribute to the development of advanced communication tools designed to enhance safety and efficiency in aviation operations.

Inclusion criteria

The inclusion criteria to take part in this study are:

- Be 18 years old or older
- Be fluent in English (note that this study is conducted entirely in English)
- Have Commercial pilot licence (CPL) or Airline Transport Pilot Licence (ATPL)
- Be familiar with CPDLC

Nature and duration of your participation in the research activity

As a participant in this research activity, you will receive training material explaining how to use CPDLC for taxi clearance. Review this material should take less than 10 minutes. We will contact you by email to find a convenient time slot to conduct the simulator study.

On this date, you will meet the research team at Polytechnique flight simulator. We will email you all the information required to get to the flight simulator.

The test consists of a scheduled flight at Los Angeles airport (LAX). You will do 6 taxi scenarios from push-back to takeoff clearance. You will act as the Pilot Non-Flying (PNF) and a member of the research team will act as the Pilot Flying (PF). During each scenario, you will interact with an advanced taxi navigation system integrating Controller Pilot Data Link Communication (CPDLC) and an Airport Moving Map (AMM). You will be required to respond to and execute taxi clearances provided through the CPDLC system.

After each scenario, we will ask you to complete the following questionnaires:

- NASA TLX for workload assessment
- Situation Awareness Global Assessment Technique (SAGAT) for situation awareness
- System Usability Scale (SUS) and User Experience Questionnaire (UEQ) for usability
- We will also do screen capture of the CPDLC application to measure response time to clearances. We do not record video from the flight simulator, nor from the participants. At the end of the session, we will conduct a debriefing interview to collect your feedback on the CPDLC application.

It is important to note that we are evaluating the usability of the CPDLC application, and we need your participation to do so. We are not evaluating your performance as a pilot. It is totally normal that you may commit errors during the test. This reflects a problem with the CPDLC application and not with your performance as a pilot.

The total duration of your participation is expected to be 180 minutes, including a briefing, the simulation exercises, and a debriefing session.

Risks that may arise from your participation in the research activity :

This activity should not entail greater risks than those encountered in your daily life.

Disadvantages that may arise from your participation in the research activity

The main inconvenience of participation is the time required to carry out all the scenarios in the study. To do the best, the researcher will finish the experiment in 180 minutes (i.e. 3 hours), with a five-minute break between each scenario.

Benefits that may arise from your participation in the research activity

This experiment offers a valuable opportunity to test a data link system, which has significant implications for the future of the aviation industry. By participating, individuals will contribute to advancing the state of knowledge regarding the integration of data link system integrated with airport moving map technology.

Financial compensation

Participants in the study will receive a \$50 compensation for their time offered in cash. You will also receive a parking ticket to Polytechnique to ensure convenience.

Voluntary participation and possibility of withdrawal

Your participation in this research activity is voluntary. You are therefore free to refuse to participate and can at any time decide to withdraw without having to justify your decision and without risking suffering any prejudice. All you have to do is inform a member of the research team, by simple verbal notice.

In the event of withdrawal, you can request the destruction of the data concerning you. However, it will not be possible to remove your data or material from the analyzes conducted once they have been published or disseminated.

The research team and the research ethics committee reserve the right to remove participants from the study if they do not follow the instructions, if there are administrative reasons for abandoning the activity, or for all other reasons regarding the feasibility of the study. If such a situation arises, the research team will inform you as soon as possible.

Confidentiality and protection of your data

The research team will collect and record all your data in a secure manner to protect its confidentiality.

Here is how we will protect your data during data collection:

The experiment will take place at Polytechnique Montreal in a flight simulator. Only the members of the research team identified at the beginning of this form will be allowed to access the room during the experiment.

All the data recorded will be kept on Polytechnique Montréal's secure server, accessible by password only to researchers identified at the beginning of this form. No copies are kept on researchers' computers.

The personal information allowing an indirect identification are: age, position occupied by the participant, number of years in this position, total flight hours, planes flown, known taxi assistance equipment, as well as the airports most familiar with.

Personal information is recorded in a separate file protected by a password and is kept on Polytechnique Montréal's secure server, accessible by password only to researchers identified at the beginning of this form.

Here's how we'll protect your data during analytics and data transfer between team members:

In order to preserve your identity and the confidentiality of this information, we will encode the data: each participant receives a unique code (ex. P1) and the data collected is filed with this code.

Here's how we'll protect your data during result publication:

When the results are published, the data will be presented in such a way that individuals cannot be identified.

Finally, here is how we will protect your data after the research project:

Your data will be kept by the research team for 10 years after the end of the research project and will be destroyed after this period.

You have the right to view your research data profile to verify the accuracy of information gathered for as long as the research team or Polytechnique Montréal have said information. Note however, that in order to preserve the scientific integrity of the research project, some information will only be accessible upon the research project's completion.

Dissemination of research results

You can view the results of this study by reading the public summaries and research articles published on Professor Doyon-Poulin's web page at <https://www.polymtl.ca/expertises/doyon-poulin-philippe> Research results will not be commercialized. Data from research activity may be published in scientific journals or shared with others in scientific discussions. However, no publication, scientific communication or commercialization of research results will contain information that could lead to your identification.

Compensation in case of damage and rights of participants

If your participation in the research project results in any injury whatsoever, you in no way waive your legal rights, nor relieve researchers, funding organizations, and Polytechnique Montréal of their professional and legal responsibilities.

Contacts

If you have any questions about the scientific aspects of the research project or to withdraw from the study, you can contact Philippe Doyon-Poulin using the information at the beginning of this form.

For any concerns about your rights or the responsibilities of the research team regarding your participation in this project, you can contact Polytechnique Montréal's Research Ethics Committee at (514) 340-4711, extension 4420 or by email to ethics@polymtl.ca

Consent to participation in a research project

I have read and understood the attached documentation, which describes the nature and the process of the research project, as well as the risks and inconveniences that this project may incur.

I understand that I have the right to satisfactory answers in response to any questions that I have in regard to my involvement in this project, and this, throughout my participation therein.

I freely consent to participation in this research project, after having had the time to consider it, to my complete satisfaction. I confirm having felt no pressure to participate.

I understand that as a participant in this research project, I do not renounce any of my rights, nor do I waive researcher's legal responsibilities.

I understand that I can consult the research data profile that the research team has created with my data.

I can, at any time, with verbal warning, decide to immediately cease participation, and that at that time, I will immediately be freed from my commitment.

I have received a copy of the present document.

Participant's first and last name

Participant's signature

Date :

Research team commitment

I hereby confirm that I myself, or a representative, has explained to the above-mentioned individual the nature of their participation in the present research project, have asked if they have questions, and have answered any questions posed. I or we have clearly indicated that the individual remains free to cease participation in the study at any time, via simple verbal notification. I, along with the research team, commit to respecting the modalities described in the present consent and information form, and I declare having provided a signed copy of the latter to the individual concerned.

First and last name of research team member

Signature of research team member

Date: