IMPLEMENTATION AND VALIDATION OF TAXI-CPDLC FUNCTIONALITY WITHIN THE EU PROJECT EMMA2

Thomas Ludwig, Marcus Biella, Klaus Werner, Jörn Jakobi, Michael Röder
DLR Institute of Flight Guidance, Braunschweig, Germany

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Abstract

The first part of this paper will describe how one of the higher services of A-SMGCS, the Controller Pilot Data Link Communication (CPDLC) Ground Clearances Function (TAXI-CPDLC), was implemented at two ground sites (Prague-Ruzyně and Milano-Malpensa) and the airborne site. It describes the basic principles and approach for the message definition and both the software and the hardware implementation into the real time simulations and on-site trials.

The second part will focus on the results of the validation study that was conducted with eight commercial airline pilots at DLR's Generic Experimental Cockpit. It was demonstrated that requirements from the operational concept were mostly fulfilled while pilots. Furthermore, effects on Situation Awareness and workload were tested.

1 Introduction

Within the Sixth Framework Programme the European Commission founded the integrated project EMMA (2004-2006) to harmonise the implementation of the first two levels of an Advanced Surface Movement Guidance and Control System (A-SMGCS), with focus on surveillance and conflict monitoring, and to further mature the necessary technology and operating procedures. The subsequent second part of the project, called EMMA 2 (2006-2009), set itself the goal of developing, implementing and testing operational concepts for higher-level A-SMGCS services, like planning, routing and guidance via data link communication, with the main focus on planning support to controllers and advanced onboard guidance support to pilots.

2 CPDLC Implementation

One elementary component for reaching a higher level of A-SMGCS will be Controller Pilot Data Link Communication (CPDLC) for ATC purposes on ground of the airport (TAXI-CPDLC). The operational concept for TAXI-CPDLC has been developed by the EMMA2 SP1 Operational Concept Team [5]. The technical concept is based on a direct communication between the flight crew and its current ATC authority by data link, using VDL-2 and ATN, a technology currently introduced in Europe by the EUROCONTROL LINK 2000+ initiative for the introduction of data link for ATC purposes.

2.1 Definition of Taxi CPDLC Messages

Since EMMA2 was a research project, it should strive for innovative and forward-looking concepts. Thus when defining new message elements for the future TAXI-CPDLC service the following was considered:

Intended use: The applications for which the messages are intended should be defined.

Completeness: All applications in the area of interest should be covered. For the use of CPDLC in an A-SMGCS this means, that all phases of flight should be covered, in which the aircraft is under control of the tower. As far as possible all required message elements should be defined.

Extensibility: The introduction of TAXI-CPDLC as a new service could start with a limited functionality and be enlarged step-wise, in order to avoid an increase of workload for the users in the beginning and thus endanger the acceptance for the new service. Therefore it should be possible, that in the beginning of the implementation phase for TAXI-CPDLC only a subset of the defined applications will be used, and the applications can use also a subset of their defined messages. With such a step-wise approach the use of the defined applications as well as of their messages can be extended along with their proven applicability as well as growing acceptance and operational needs, without the necessity to completely redefine the message set.

The existing CPDLC message set defined by ICAO reflects the phraseology used in verbal communication and covers mainly clearances for en-route control, apart from some messages, which are suitable also for ground use. In order to use CPDLC in A-SMGCS (TAXI-CPDLC) the existing message set has to be extended by ground clearances and ground specific information messages.

As EMMA2 aimed at a Europe-wide harmonisation of the A-SMGCS concept, also the TAXI-CPDLC implementation task strived for a harmonized solution. Taking into account the ICAO standard as the basis and the EUROCONTROL CASCADE OFG D-TAXI project conducted at the same time, the EMMA2 message element definitions for TAXI-CPDLC are based on:

- Messages from the ICAO message set defined in the documents 9694 [2] and 4444 [3], as far as they are suitable for TAXI-CPDLC.
- The message definitions from the CASCADE D-TAXI OSED [4] as the main basis: the CASCADE Operational Focus Group (OFG) has already performed a lot of work here and feedback from field trials has been considered.
- Messages from the D241_FRD_CPDLC document [5] compiled for EMMA (1) on-board implementation team. In this document a working team consisting of Airbus (AIF), TATM and DSNA had defined a compact taxi message set as a first step for the implementation of TAXI-CPDLC. This message set was then updated by the EMMA2 on-board implementation team.
- Further message elements, which deemed to be necessary and useful in the future, were defined by EMMA2 Operational Concept Team [5].

Air-ground communication via the ATN makes obligatory use of the *ASN.1 PER* (Abstract Syntax Notation One, Packed Encoding Rules) encoding rules for encoding of the CPDLC messages. A key element in a message definition and encoding via *ASN.1 PER* is the message element identification number (in short: message number), which is the basic means for encoding the message. It must be unique throughout the whole message set. Two CPDLC message subsets have been defined by ICAO: One for uplink and one for downlink. The allocated message numbers for uplink and downlink are not required to correspond.

Defining new message elements and allocating message numbers to them requires to regard the existing ICAO message elements and their message numbers.

The existing CPDLC ATN SARPS message set definitions comprise an “extensibility marker”, which makes it possible to add new message elements and message numbers. The respective syntax provides a specific encoding, which prevents existing decoders to get out of synchronisation, when they try to decode a new and for them unknown message.

Current implementations support uplink messages with message numbers from 0 to 236 and downlink messages with numbers from 0 to 113. If a message is not defined in their implemented ASN.1 decoding rules, when for example a message 257 is received, the decoder will be able to ignore it. Without the extensibility marker, the decoder would fall out of synchronisation, the message would be rejected and the communication aborted.

When implementing new messages for new ATN end applications, there are different possibilities, which have been used and tested in other data link projects:

- Making use of the so-called "free text" messages. There are currently 11 downlink and 16 uplink free text messages defined by ICAO for non-specified use by applications. During the communication of a new message the message content will be packed into the string element of such a message, and at reception unpacked from it. The advantage of such an approach is that existing applications, which do not 'understand' the new messages, may be capable to display them. The disadvantage is that only text data can be communicated, and that no real encoding and thereby compression of the payload is performed, which is against the ATN philosophy.
- Defining new messages with new message numbers. This will make use of the inherent extensibility of the ATN CPDLC message set, provides compression and thus is well in line with the ATN philosophy.

When reviewing existing ICAO CPDLC messages which might be suitable also for TAXI-CPDLC, the message parameters have to be checked carefully against the ASN.1 declarations. Mostly a TAXI-CPDLC message will require different parameters, e.g. the uplink message 118 "AT (position) CONTACT (unit name) (frequency)" would require an airport location instead of an en-route position. Unfortunately the ASN.1 definition for "position" is neither usable for TAXI-CPDLC nor extensible, and thus message element 118 cannot be used.

ASN.1 parameter definitions are very strict, and some are defined for extensibility, but others not. String values currently allocated to en-route parameters are often restricted to a short size and thus can not be reused.

The complete message set for TAXI-CPDLC as well as example procedures for inbound and outbound flights can be found in the suitable documents on the official homepage of the EMMA2 project:
http://www.dlr.de/emma2/.

2.2 The Experimental System

The VDL-2 radios were configurable multimode radios from SELEX, type "OTE DTR100 V". These integrated multimode radios comprise software controlled transmitters and receivers especially for VHF band ATC applications. Their architecture is optimised for VDL digital modes, in particular for modes 2 and 4, in which stringent requirements about turnaround times, from TX to RX and vice-versa, have to be fulfilled.

The ground station radio was configured and controlled by the ground station controller. In contrast to a commercial avionics implementation, at the onboard side also a multimode radio was used, which gets its set-up and control by the airborne simulator, and thus behaves like an onboard VDL-2 transponder.

Also at the onboard side no commercial Communication Management Unit (CMU) was used, which would have the ATN stack and the communication functions implemented. Instead, like on ground, a Data Link Communication Unit (DLCU) was used, which comprises an Application Interface Server and the ATN stack. This configuration provided an open architecture and thus the possibility to implement the TAXI-CPDLC functionality. The respective technical solution both for the ground and the onboard side was developed by AIRTEL ATN.

At the onboard side the TAXI-CPDLC end applications were the Cockpit Display of Traffic Information (CDTI, see Fig.1), used as the pilot communication interface and an on-board Electronic Moving Map Display, used for the graphical presentation of the received taxi route.

Fig.2 shows the functional architecture of the EMMA2 TAXI-CPDLC implementation for Prague-Ruzyně and Milano-Malpensa. The left side of the figure shows the airborne system configuration, whilst the right side shows the ground system configuration.

Fig. 1: Airworthy CDTI, modified for TAXI-CPDLC use

The CDTI is a commercial multi-functional display system manufactured by Funkwerk-Avionics, which can be used for visualisation of various information as well as maps, see Fig.2. In the case of EMMA2 it was modified for displaying the TAXI-CPDLC messages exchange only.

The implementation of TAXI-CPDLC in an A-SMGCS required also the availability of other automated high-level services, which release the ATCO as far as possible from the manual composition of messages, in order to avoid the respective workload and keep the time required for manual inputs into the system as low as possible. Therefore at the ground site the TAXI-CPDLC end application was integrated with the Electronic Flight Strip System developed by Park Air Systems (EFS; see Fig. 3), which provides HMIs for the Clearance Delivery Dispatcher (CDD), the Ground

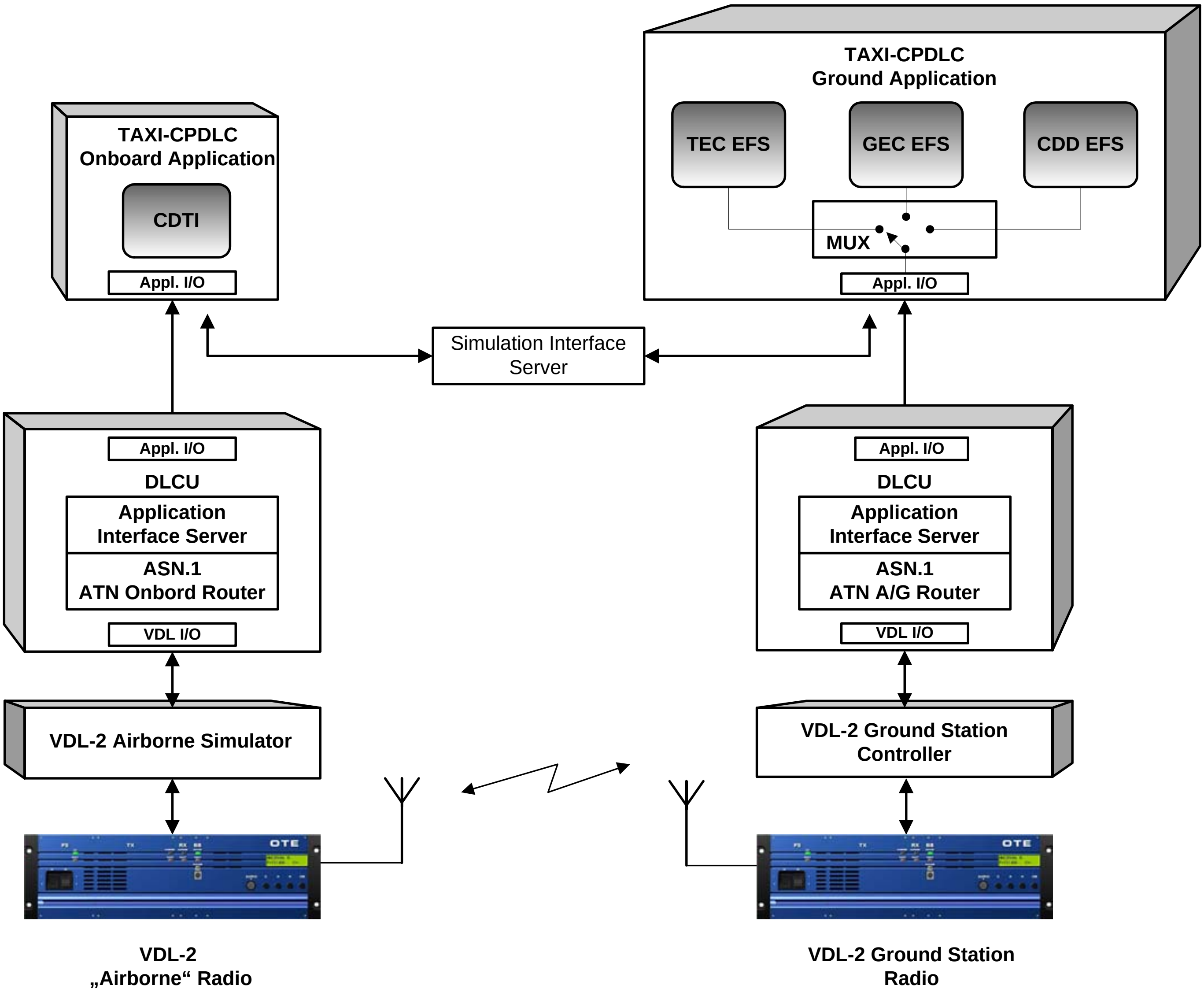

Fig. 2: Functional Architecture of the TAXI-CPDLC Implementation

Executive Controller (GEC) and the Tower Executive Controller (TEC). The abbreviations TEC, GEC and CDD are Prague-specific, but will be used in the following descriptions.

For simulation purposes the onboard and the ground application were connected via a simulation interface. In the simulation it was not required to use the full communication path via ATN stack and radio transmission.

Due to the fact that Prague-Ruzyně and Milano-Malpensa did not have a CPDLC implementation in the approach centre, no transfer of communication from Approach to Tower could be performed. As a consequence, only a local ATN implementation at the airport, without ground-to-ground routing between Approach and Tower was there.

Fig.3: Electronic Flight Strips (EFS) and Message Window for DLR test aircraft D-ADAM, CPDLC is "on"

The TAXI-CPDLC ground application was a single entity, with respective modules integrated in the EFS components of Clearance Delivery, Ground and Runway/Tower Control. Transfer of communication was going along inside the EFS with transfer of control, i.e. as a flight strip is handed over from one EFS display to another, also the communication path for the respective aircraft was switched over to the communication module of this EFS display. This is illustrated in Fig.2 by the "MUX" multiplexer component.

The interface between the ATN communication stack and the TAXI-CPDLC end applications consisted of an Application Interface Server, which comprises a TCP server for the LAN based data exchange with the TAXI-CPDLC end application client. The advantages of using a server-client based architecture are the following:

- The applications and their interfaces can be developed independently of the development and implementation of the ATN stack.
- The end application clients may run on other computers, and under other operating systems.
- Other end application clients may access the data in parallel, e.g. for data logging or monitoring.
- For simulation purposes the onboard and the ground CPDLC End Application clients can be easily connected via a simple Simulation Interface Server, without the necessity to implement the ATN stack.

Fig.4 shows the block diagram of the interfaces.

Received ASN.1 coded CPDLC messages were decoded inside the ATN stack and provided as human-readable ASCII text to the end application (EFS on ground, CDTI on board). For messages to be transmitted, the human readable ASCII text messages from the end applications were encoded inside the ATN stack into ASN.1 coded CPDLC messages and the sent via VDL.

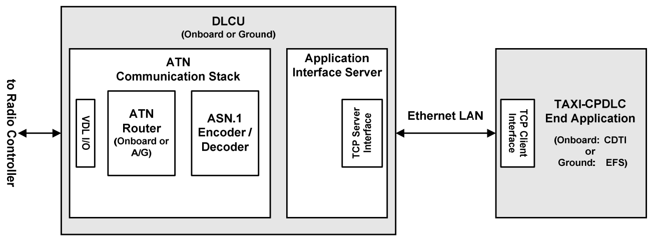

Fig.4: ATN Interface for Onboard and Ground Application

The VDL-2/ATN data link initialised automatically and as soon as a connection between the ground station radio and the onboard radio existed, the end application was notified, that a logon was possible. The ground end application was informed periodically, whether a data link connection to an aircraft existed or not, and further whether the aircraft was logged on. After the connection to an aircraft ended, one last message for this aircraft notified the end of the connection.

2.3 Implementation and Verification Results

The TAXI-CPDLC service provided the transmission of pilot's clearance requests and acknowledgements from air to ground (downlink) as well as the transmission of clearances from ATC to the aircraft (uplink). The TAXI-CPDLC service supported only non time-critical clearances, i.e. start-up, pushback, taxi and handover. Time-critical clearances like crossing, line-up and take-off were issued via voice radio. Consequently the service was available for CDD and GEC only, whilst the TEC operated in the traditional way via voice communication.

The TAXI-CPDLC service was operated by the controller via the EFS. A green CPDLC marker at a flight strip indicated that the respective aircraft was logged on and thus able to receive and transmit data link messages. When the pilot of an aircraft was requesting a clearance via data link, the clearance button on the respective flight strip was highlighted. As soon as the controller decided to issue the clearance, he clicked the clearance button and the clearance was automatically transmitted to the aircraft via data link. After that the colour of the button turned to blue. The taxi route to be transmitted was shown in the EFS routing field by text.

Voice communication via R/T was always the back-up. Voice communication should be used if any additional information exchange is necessary or in case of safety- or time critical situations.

Beside the CDTI as interface to the TAXI-CPDLC service for the on-board side, the taxi route clearances received via data link were graphically presented in the airport map on the Navigation Display in the cockpit. The taxi route was presented by a yellow line, which turned to green as soon as the PNF acknowledged the taxi clearance by pressing the WILCO-button at the CDTI.

The technical feasibility of a CPDLC communication via VDL-2 on ground was proven and new message sets were defined and their encoding with *ASN.1 PER* and their transfer were successfully tested in the simulation and in on-site trials in Prague and in Malpensa. Several in- and out-bound taxi scenarios were realized with the only use of TAXI-CPDLC.

The data link connection was stable during the whole test period and all instructions were transferred error free and with latencies smaller than one second. The data link and the procedures were accepted immediately after the first trials; therefore the pilots and controllers used TAXI-CPDLC in all subsequent trials without voice.

During subsequent airfield circuits also range tests were accomplished for the establishment of the data link connection.

3 Validation

Beyond technical tests, validation activities aim to check a) the **operational feasibility** in terms of users' acceptance and b) **operational improvement** e.g. in terms of safety, human factors. The validation guideline E-OCVM by EUROCONTROL was applied to guarantee that all relevant validation sub-steps were performed [7]. First, a generic validation test plan was developed which was used by local validation teams (e.g. Milan, Braunschweig) as basis for compiling there own specific validation test plan [8].

The series of tests started with real-time simulations at DLR-Braunschweig's Generic Experimental Cockpit (GECO) and Apron and Tower Simulator (ATS). Here the whole system was validated while pilots and ATCOs used the higher A-SMGCS services mentioned above. But it should stated clearly, that even though simulation re-creates a realistic environment, and permits the safe testing of safety-critical events and the repetitive testing of rare events, subsequent operational trials must be performed to prove the operational feasibility of new standards and procedures under real life conditions. Therefore the real-time simulations mentioned above were a preparatory step for the on site trials at Prague-Ruzyně Airport and Milano-Malpensa Airport as well, when the test aircraft ATTAS was aimed at validating the higher A-SMGCS services under real operational conditions.

3.1 Results from On-board Real Time Simulations

3.1.1 Method

Participants: In the Operational Improvement Studies eight male pilots took part, seven of them were commercial airline pilots. Their average age was 42.4 years (standard deviation=15.3) and the mean reported flight hours were 7471 (standard deviation=7731) [9].

Equipment: The study took place in DLR's fixed-base flight simulator Generic Experimental Cockpit (GECO). It is designed on the Airbus A 320 architecture using the flight dynamics of the VFW614 in a fly by wire version.

Scenarios: Each pilot flew a total of eight experimental scenarios, four of them as Pilot Flying resp. as Pilot Non Flying. Scenarios consisted of an inbound and outbound leg including taxiing on Prague Ruzyne airport under CAT I visibility conditions. Four different test conditions were applied: Baseline, Electronic Moving Map (EMM), EMM plus GTD (Ground Traffic Display), EMM plus GTD and standard TAXI-CPDLC, EMM plus GTD and advanced TAXI-CPDLC including a clearance update by the Ground Executive Controller. In these sessions, a controller team from the Prague ANS CR (Air Navigation Services of the Czech Republic) was responsible for ATC using DLR's Apron and Tower Simulator (ATS) which was connected to the GECO. Together with other traffic steered by pseudo pilots, the GECO operated in the scenario simulated by the ATS. The complete procedures are described in [9].

A further aspect of investigation was, whether before-hand information might help the pilot with the preparation of ground navigation. Thus the EMMA-2 A-SMGCS provided information about the expected taxi route, for outbound flights after the departure clearance had been issued, and for inbounds before final approach.

3.1.2 Assessment of Operational Feasibility and Operational Improvement

Operational Feasibility via tailor-made questionnaire: A tailor-made questionnaire was created to check the fulfillment of the requirements basing on the description in the Systems, Procedures and Operational Requirements document of EMMA2. Each of the 72 items has a six point Likert scale ranging from from 1 “strongly disagree” to 6 “strongly agree”. After finishing off all of test runs, the questionnaire was given to the pilots. Their response reveals if basic requirements are fulfilled if an on-board taxi guidance system is in use [8].

Operational Feasibility via Standard Usability Scale (SUS): The SUS [10] was given to the pilots after the very last trial. Answers range from 1 “strongly disagree” to 5 “strongly agree” on a five point Likert scale. After finishing off all of test runs, the SUS was given to the pilots. Their response reveals if usability in general is fulfilled if an on-board taxi guidance system is in use [8].

Operational Improvements via tailor-made questionnaire: an additional tailor-made questionnaire was created to check the operational improvements e.g. in terms of safety basing on the “expected benefits” that were identified in EMMA2's “Systems, Procedures and Operational Requirements” document (www.dlr.de/emma2). Each item has a six point Likert scale ranging from from 1 “strongly disagree” to 6 “strongly agree”. After finishing off all of test runs, the questionnaire was given to the pilots. Their response reveals if safety increases is perceived by the pilots while using a taxi guidance system [8].

Operational Improvements via Workload and Situation Awareness questionnaires:
The Instantaneous Self Assessment Scale (ISA) was originally conceived at NATS. It was applied within EMMA2 trials twice during the inbound and the outbound segment of each test run. The scale ranges from “low” (1) to “high” (5) for workload and from “low” (1) to “high” (10) for situation awareness. Pilots were questioned approx. in the middle of the segment (e.g. after a runway cross) and at the end of the segment (before reaching the gate resp. before line-up). Pilots’ response reveals if an increase of workload resp. situation awareness is perceived by the pilots while using a taxi guidance system.

3.1.3 Results

Results to Operational Feasibility (RTS): Since the sample size is only eight different pilots per item, the binominal test as a non-parametric statistic was used to prove the results of the questionnaires for their statistical significance. Finally, 56 operational requirements or procedures could be regarded as verified, twenty of them statistically significant. The remaining 16 operational requirements were not answered positively which was caused by the use of the modified airworthy interface (CDTI) which was unfamiliar for the pilots.

For example, pilots agree that the new cockpit services were well integrated into the existing systems. This result is highly statistically significant for the GTD (M=5.38; sd=0.74; p<0.01) but only significant by trend for TAXI-CPDLC (M=3.88; sd=0.83 and p=0.07). According to the pilots the GTD is capable of being used appropriately when operating within the movement area (M=5.25; sd=1.04; p<0.01); results for the TAXI-CPDLC are positive as well (M=4.25; sd=1.28; p=0.29) but not significant [9].

SUS Questionnaire: The pilots answered all ten items in favour of the new system. Three of them became even highly statistically significant: According to the pilots there was not too much inconsistency in the system (M=2.50; sd=0.53; p<0.01). They find the system not very difficult to use (M=2.38; sd=0.92). Finally, they agree that they do not need to learn a lot of things before start to work with the system (M=1.88; sd=0.83; p<0.01) [9].

Operational Improvements Questionnaire, Sub-Scale Safety: Highly statistically significant results include that the graphical taxi clearances on the display would enable pilots to follow an assigned taxi route more safely (M=5.63; SD=0.52; p<0.01). Furthermore the indication of the surrounding traffic is an additional information source to navigate and manage the aircraft speed more safely (M=5.75; sd=0.46; p<0.01) [9].

Workload and Situation Awareness: The ISA means of each test run were analysed in a 4 x 2 (A-SMGCS treatment x pilot role) two-way repeated measures analysis of variance (ANOVA).

Regarding *workload* the ANOVA revealed a highly significant main effect of the A-SMGCS treatment (F(3,21) = 5.418; p<0.01) with a mean of M = 2.20 for the (EMM) baseline, respectively M = 2.12 for GTD and M = 2.48 for standard TAXI-CPDLC (incl. GTD) and M = 2.36 for advanced TAXI-CPDLC (incl. GTD) on a scale reaching from “under-utilised” (1) to “excessive” (5). No significant main effect could be shown for the pilot role (F(1,7) = 1.932; p = .207), both pilot flying and pilot non flying seem to have a similar level of workload. Yet there is a significance for the interaction between treatment and pilot role (F(3,21) = 3.743; p<0.05), with the highest mean M = 2.52 in the condition pilot non flying using advanced TAXI-CPLDC.

Regarding *situation awareness* the ANOVA revealed no significant main effect of the A-SMGCS treatment ($F(3,21) = .146$; $p = .931$) with a mean of $M = 8.09$ for the (EMM) baseline, respectively $M = 9.03$ for GTD and $M = 8.70$ for standard and $M = 8.74$ for advanced TAXI-CPDLC (incl. GTD) on a scale ranging from “low” (1) to “high” (10). There is no significant main effect for the pilot role ($F(1,7) = 1.337$; $p = .286$), both pilot flying and pilot non flying seem to have a similar level of situation awareness. There is no significance for the interaction between treatment and pilot role ($F(3,21) = 1.391$; $p = .273$) [9].

3.2 Results from Flight Tests (On-Site Trials)

Three DLR test pilots and one commercial airline pilot performed inbound and outbound scenarios on DLR test aircraft ATTAS in Prague and Milan-Malpensa in November 2008.

In general, the TAXI-CPDLC service worked technically perfect. There were some initial problems with respect to doubled strips on the EFS caused by successive aerodrome circuits of the test aircraft ATTAS (which were component of the flight tests to guarantee both inbound and outbound scenarios within a short time frame) and one link loss due to the ATTAS leaving the VDL-2 range, but this could be solved easily.

Pilots commented the use of the TAXI-CPDLC in a positive way as it was already done in the simulation trials. According to the pilots the system worked technically very well and will be a great step ahead in taxi procedures.

In general the principle and the concept are appreciated by the pilots.

Nevertheless, in their opinion, any CDU or keyboard will improve work with listing and sending messages on CPDLC - compared to the use of the CDTI.

Furthermore, an ATC message attention getter push-button for better crew awareness was missing in the ATTAS cockpit front panel.

The pilots stressed that these comments are associated with the experimental installation and could be easily solved more or less with today’s technology.

3.3 Discussion

TAXI-CPDLC is regarded as potential means by all pilots which will ease the crews’ work considerably.

It must be distinguished clearly between the positively rated graphical information on the EMM display and the intermingled rating of the usability of the CDTI, which served for selecting CPDLC messages to be sent and for the textual displaying of received clearances. The graphical presentation of the cleared taxi route on the EMM (compared to textual clearances on the CDTI) will enable pilots to follow an assigned taxi route in an intuitive way. Debriefing revealed that TAXI-CPDLC operations with the CDTI require too much head down times; this explains the increased workload in the ISA measurements. Both CM1 and CM2 stress that the displayed graphical clearances on the ND will increase situation awareness if EMMs with data link capability are in operational use. It was stated that only the novelty of the CDTI caused more head down times which might cause that either the aircraft needs to be stopped (time is lost) or redundancy of the CM2 (who additionally to his normal tasks has to operate the CDTI) is lost.

It should be stressed that use of the CDTI was necessary in the studies because this certified interface was necessary for preparing and conducting the subsequent flight trials in DLR’s test aircraft with pilots and additional safety pilots which were conducted successfully [9].

Pilots stated that a preliminary taxi route will not bring added value because the assigned route can change at short notice during initial approach (inbound) or preparing the a/c for departure (outbound), and thus is not a reliable information [9].

Pilots responded that they would like to use the TAXI-CPDLC in the future and that they agree in general with its concept given and realised in EMMA2.

The positive results of this implementation and validation performed in EMMA2 are an important milestone for the further implementation of TAXI-CPDLC under the framework of SESAR.

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