Nationaal Lucht- en Ruimtevaartlaboratorium
National Aerospace Laboratory NLR

Executive summary

Evaluation of an Autonomous Taxi Solution for Airport Operations during Low Visibility Conditions

Problem area
The growing amount of air transport creates the need for more weather independent airport operations. Currently, Low Visibility Conditions have a negative effect on airport capacity. One of the reasons is the limited outside view of Ground Controllers from the control tower, which generates additional workload, and limits the number of taxiing aircraft a controller can control.
The current study considers the transfer of some of the Ground Controller tasks to the flight crew as a potential means to increase capacity. With use of additional systems in the cockpit, flight crews may be able to perform these tasks and become more independent of air traffic control while taxiing at the airport. In the ultimate case, the flight crew can operate autonomously on the airport surface, hence: autonomous taxiing.

Description of work
A flight simulator experiment has been conducted in the NLR GRACE full-flight research simulator. This experiment was used to study the potential of autonomous taxiing, with focus on taxi separation. Three different combinations of autonomy level and taxi display support have been evaluated against two low visibility conditions. The autonomy conditions consisted of either ATC or the flight crew being responsible for conflict detection and resolution. In the case where the flight crew was responsible there was no ATC present at all. The taxi display support included visualisation of the route and levels of cockpit display of traffic information and conflict alerting information.
Five flight crews existing of professional airline pilots participated in the experiment and conducted 12 taxi runs containing

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experiment

This report is based on a presentation held at the ATM 2011 conference, Berlin, 13-16 June 2011.

different conflict scenarios at Amsterdam Airport Schiphol.

Results and conclusions
The autonomous taxiing concept was evaluated with respect to safety, efficiency and acceptability, based on the objective and subjective experiment data.
The overall conclusion was that the flight crews were able to operate autonomously at the airport surface. No incidents occurred. In all cases the flight crew was able to detect potential conflicts in time and conduct a safe resolution, without this being accompanied by a significant increase in workload. The taxi displays with traffic information and conflict alerting increased the safety by providing more Situational Awareness. Nonetheless, a considerable number of undesirable situations occurred, which had a negative effect on the efficiency of the operations and thus hampered potential capacity improvement. These situations were mainly due to the uncertain intentions of other aircraft.
The pilots considered ATC to be essential, especially during LVC.

Applicability
The current study focussed on conflict detection and resolution during autonomous taxiing. The concept of autonomous taxiing is however impacted by many more aspects, like routing, the timing of operations, sequencing of the aircraft, runway crossing, etc. These aspects need further study.
The current experiment was set up as generic where the concept definition and design of cockpit support are concerned. Airport layout however has impact on possible routes, conflict situations and resolutions possible and thus influences the scenarios that can be conducted. Experiment trails on more and less complex airports than Amsterdam Airport Schiphol may give more insight in the effect of airport layout on the feasibility of the concept.

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Evaluation of an Autonomous Taxi Solution for Airport Operations during Low Visibility Conditions

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Summary

The growth in air transport creates the need for weather independent airport operations. Currently, Low Visibility Conditions have a strong negative effect on the airport capacity. One of the reasons is the reduced capacity of Air Traffic Control. Due to the limited outside view of Ground Controllers from the control tower, additional workload is generated, which limits the number of taxiing aircraft a controller can control. Transferring some of the tasks of the controller to the flight crew is therefore seen as a potential means to increase capacity. Enhanced taxi display systems in the cockpit may enable this. In the ultimate case, the flight crew can operate independent of Air Traffic Control; hence autonomous taxiing. This paper discusses the potential of autonomous taxiing with a focus on taxi separation. An experiment was conducted with different taxi display systems and Alert Levels to evaluate the concept with respect to safety, efficiency and acceptability. The results indicate that improved taxi displays increase the safety by providing more Situational Awareness and may enable taxiing without Air Traffic Control support. A considerable number of inefficient situations occurred though, mainly due to the uncertainty about intentions of other aircraft. Furthermore navigation errors occurred that may be prevented by route deviation alerting. Both indicate areas for improvement.

Contents

Nomenclature

t_{CPA}	=	time to closest point of approach, s
p	=	significance, -
r	=	effect size, -
μ	=	mean
σ	=	standard deviation

Abbreviations

AAS	Amsterdam Airport Schiphol
ADS-B	Automatic Dependent Surveillance - Broadcast
AL	Alert Level
AMM	Airport Moving Map
ANOVA	Analysis of Variance
A-SMGCS	Advanced Surface Movement Guidance and Control System
ATSA-SURF	Enhanced Traffic Awareness on the Airport Surface
CD&R	Conflict Detection & Resolution
CDTI	Cockpit Display of Traffic Information
CPA	Closest Point of Approach
CPDLC	Controller-Pilot Data Link Communication
DCDU	Data link Control and Display Unit
EFB	Electronic Flight Bag
GC	Ground Controller
HMI	Human Machine Interface
LVC	Low Visibility Conditions
ND	Navigation Display
NLR	National Aerospace Laboratory
NOTAM	Notice To Airmen
PF	Pilot Flying
PFD	Primary Flight Display
PNF	Pilot non-Flying
PZ	Protected Zone
R/T	Radio Telephony
RVR	Runway Visual Range
SA	Situational Awareness
TMX	Traffic Manager

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I. Introduction

Low Visibility Conditions (LVC) have a large negative effect on the ground control capacity at airports and are a cause for delays. LVC apply when the meteorological conditions are such that all or part of the manoeuvring area cannot be observed from the control tower. Low Visibility Procedures (LVP) have to be conducted [1] which drastically reduces capacity, as illustrated by Figure 1 for Amsterdam Airport Schiphol (AAS) [2]. During LVC the Ground Controller (GC) is unable to monitor and control ground traffic on the basis of visual surveillance from the control tower. Additional support systems (like Surface Movement Radar or multilateration) and a more active control of traffic (more position reports between pilot and GC) are used to compensate for this. Both of these measures have a negative impact on the GCs workload and limit the number of aircraft a GC can control at a time. This is one of the reasons for decreased airport capacity during LVC.

In line with the above, a means to improve airport capacity during LVC is sought by transferring some of the GC tasks to the flight crew. Enhanced taxi display systems in the cockpit are expected to enable this and allow the flight crew to operate more and ultimately fully independent of Air Traffic Control (ATC). Additionally, the flight crew only having to monitor and control the ownship might result in more efficient operation.

This paper discusses the potential of such a fully autonomous (no ATC) taxi solution, with a focus on taxi separation, based on a human-in-the-loop flight simulator experiment.

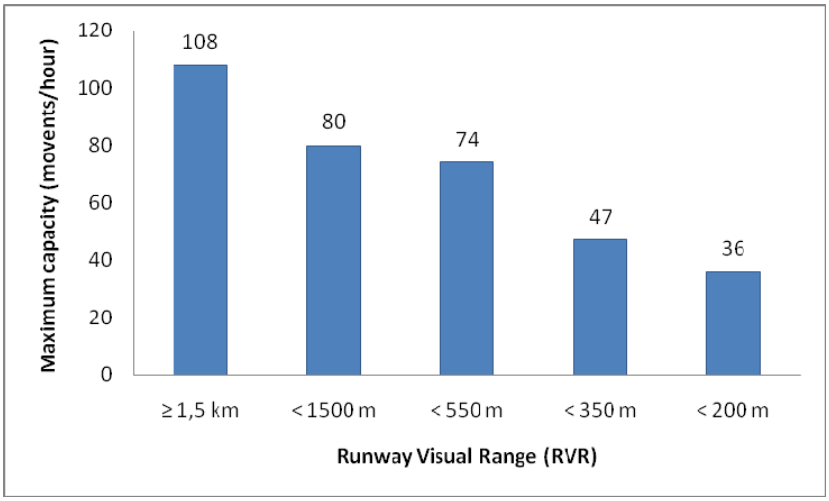


Figure 1 Impact of poor visibility on the capacity of Amsterdam Airport Schiphol

II. Background

The desire to have a safer and weather independent airport throughput has led to the development of new technologies, incorporated in an overall Advanced Surface Movement Guidance and Control System (A-SMGCS) [3]. A-SMGCS supports controllers, pilots, and vehicle drivers in their surveillance, control, routing, and guidance tasks at the airport [4].
The Airport Moving Map (AMM) is introduced in the cockpit, as part of A-SMGCS. It provides a depiction of the position and orientation of the ownship on a digital airport map, containing all the relevant airport elements (Figure 2). Previous research has shown that such a map increases the pilot's Situational Awareness (SA) during taxiing [5,6] whereas the workload decreases [5,6,7]. Increased efficiency is obtained by means of increased taxi speeds [7] and fewer navigation errors, without a significant increase in head-down time [8]. Further improvement is obtained by addition of a taxi route presentation on the AMM [9,10].

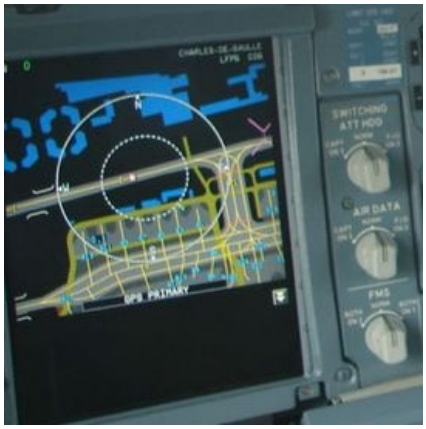


Figure 2 AMM example

Controller-Pilot Data Link Communication (CPDLC) is another new technology that effects ground operations. It uses short alphanumeric messages instead of Radio Telephony (R/T). Pilots argue that CPDLC leads to a workload reduction. Drawbacks however are an increase of response times and the missing 'party line' information that provides additional SA [11]. Nonetheless, data link messages are seen as the future means to provide all non-time critical clearances during ground operations. CPDLC also offers the ability to send graphical route information that can be used to visualize taxi instructions on the AMM.

Automatic Dependent Surveillance - Broadcast (ADS-B) supports other surveillance applications, like Enhanced Traffic Awareness on the Airport Surface (ATSA-SURF) [12]. With use of ADS-B aircraft automatically transmit and/or receive data such as identification and position. ATSA-SURF combines this information with an AMM and presents it by a Cockpit Display of Traffic Information (CDTI) to provide enhanced SA of all traffic.
These new technologies have been designed to increase the safety, efficiency and capacity of airport operations. They also allow flight crews to operate less dependent of ATC, by reducing the necessity to repeatedly request route and traffic information.

III. Concept

The autonomous taxi study evaluates a concept in which the flight crew is provided with all necessary information to safely taxi to a designated point without support from ATC.

A Autonomous taxi definition

Full autonomy implies that the flight crew has full responsibility for their taxi manoeuvres and separation. ATC provides a destination 'clearance' to the runway or gate for the departing or arriving aircraft respectively, via R/T or datalink. The flight crew is responsible for arriving at this destination in a safe and efficient manner. Time constraints and sequencing are not considered in the current study.

B Flight crew tasks and support needs

In the autonomous taxiing concept, the current day ATC tasks of guidance, monitoring and alerting become flight crew tasks. The task of the Pilot Non-Flying (PNF) to communicate with ATC ceases to exist. Instead, the PNF can be more actively involved in navigation and surveillance and assist the Pilot Flying (PF).

Additional support information is essential to compensate for the missing ATC and the limited outside view (LVC). Both global and local position awareness are important for navigation and guidance of the aircraft, [6,7], and the AMM is a proven means to increase this position awareness. The taxi route must be determined in time, so that the aircraft can be controlled along this route, without unnecessary braking or stopping. This requires an onboard navigation system that contains a planning function; manual planning would be time-consuming and inefficient. From the aircraft's position and destination combined with an airport database, the most optimal taxi route can be derived. This requires an up-to-date database and digital Notice To Airmen (NOTAM) information. The route can graphically be provided to the flight crew on the AMM.

During taxiing, conflicts with other traffic may arise. In order to detect these conflicts, the flight crew must have sufficient SA with respect to the surrounding traffic. Three types of conflicts can be distinguished: crossing, in-trail and head-on (Figure 3). Head-on conflicts cannot be solved and should be avoided by taking into account one-way rules in the route planning. Detecting other aircraft based on visual observation requires 400m RVR [3]. Taxiing under worse conditions therefore necessitates additional support. CDTI could provide the required information to monitor other traffic. For conflict alerting additional system functionality would be required to inform the flight crew of the identity (and severity) of the conflict.

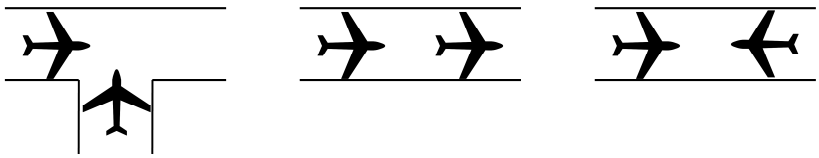


Figure 3 Illustration of different conflict situations

To resolve conflicts during taxiing, the heading can only be changed if the airport infrastructure allows this. Therefore, in general one of the aircraft has to adjust speed to give way to the other. Hence the minimum information required to solve a conflict is to know who has right of way. An external source could be used to provide this information, or else commonly known traffic rules are required.
As a final requirement, the implementation of the full autonomous taxi concept as described demands that all aircraft are is fitted with ADS-B surveillance technology in order to have a complete picture of the surrounding traffic.

IV. Experiment design

The support requirements are collected in a taxi display system, used as the basic support means in the initial concept evaluation. The evaluation aims to study the influence of autonomy (ATC or flight crew) and different levels of taxi display support. For the sake of practicality, these variables have been combined in three 'autonomy levels' as defined below and summarised in Table 1.

A. Autonomy level 0

Autonomy level 0 is the baseline situation, comparable to current day operations where ATC is in control (no autonomy). In this condition a basic taxi display is used, presented on the Navigation Display (ND). It consists of an AMM and a depiction of the taxi route clearance as provided by ATC. The AMM presents the airport elements as derived from an Aerodrome Mapping Database [13] required to provide guidance to the flight crew [14]. These elements are positioned with respect to the ownship and scaled according to the ND settings. The taxi route is uplinked via a CPDLC and consists of an alphanumeric and graphical part. The alphanumeric message is shown on the Data link Control and Display Unit (DCDU). The graphical message contains a list of waypoints representing the taxi route from the ownship position to the destination, which is used to display the route as a green line on the AMM as illustrated by Figure 4. Other communication with ATC is done via R/T.

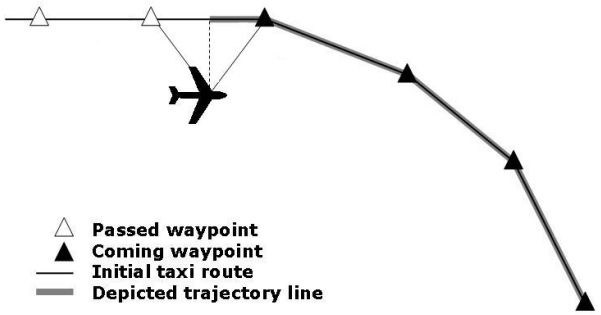


Figure 4 Representation of the taxi clearance, illustrating the part of the taxi clearance depicted on the taxi display

B Autonomy level 1

In the condition of autonomy level 1, the flight crew is responsible for Conflict Detection & Resolution (CD&R) and there is no ATC support other than the provision of the destination 'clearance' via datalink. The taxi display is that of autonomy level 0, enhanced by CDTI. Other aircraft are presented by white aircraft symbols with identification and ground speed indication; see Figure 6a).

C Autonomy level 2

Autonomy level 2 builds on autonomy level 1 with additional conflict alerting functionality. The flight crew is alerted when other aircraft are at close range or conflicts are predicted in the near future, based on a basic Closest Point of Approach (CPA) algorithm [15]. The CPA algorithm uses Protected Zones (PZ) around all aircraft, based on their size plus a safety margin of 6.25 [m]. The values are empirically determined and may need to be adjusted through a sensitivity study. A predicted separation loss of two PZs is defined as a conflict. To detect conflicts, the CPA is determined for each aircraft pair using their state-vectors, as illustrated in Figure 5. If the predicted PZs overlap at the CPA, the time to CPA, tCPA, determines the severity of the conflict. Three alert levels (AL) have been defined, see Table 2. AL 0 is used to indicate that there are no conflicts (tCPA ≥60).

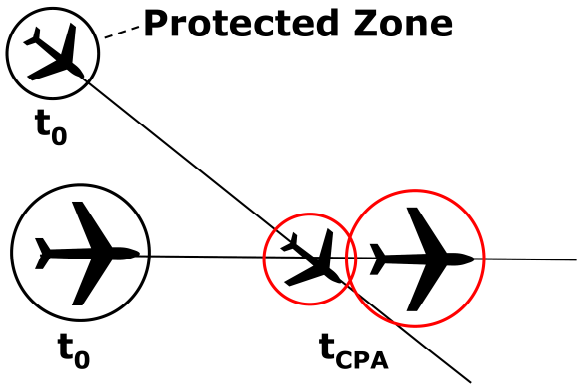


Figure 5 Schematic illustration of the state-based CPA conflict detection

1. Alert level 1

AL 1 requires crew awareness and may require crew action. A range criterion of 150m is used to provide SA for nearby aircraft that are no direct threat and alerts are given for predicted conflicts within 60 seconds. The concerned aircraft are coloured yellow on the CDTI.

2. Alert level 2

AL 2 requires immediate crew awareness and may require compensatory action by the flight crew. Alerts are given for predicted conflicts within 30 seconds. The intruding aircraft are coloured amber on the CDTI and an aural attention getting sound (‘beep’) is provided.

3. Alert level 3

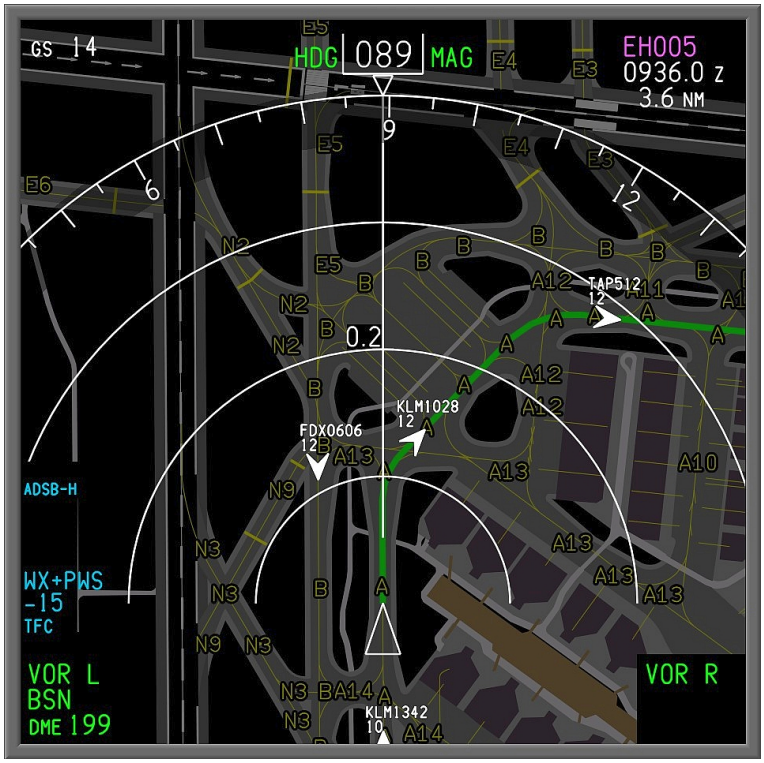
AL 3 requires immediate compensatory action by the flight crew. Alerts are given for predicted conflicts within 10 seconds. The intruding aircraft are coloured red on the CDTI and a red coloured message ‘TRAFFIC’ is shown on the Primary Flight Display (PFD) together with a ‘TRAFFIC’ callout, see Figure 6b.

Table 1 Overview of the autonomy levels applied

Autonomy condition	CD&R by	HMI support
Autonomy level 0	ATC	AMM
Autonomy level 1	Flight Crew	AMM + CDTI
Autonomy level 2	Flight Crew	AMM + CDTI + conflict alerting

Table 2 Alert Level criteria.

	Alert requirement	Symbol color	Aural alert
AL 0	-	white	-
AL 1	$t_{CPA} < 60$ sec or separation < 150 m	yellow	-
AL 2	$t_{CPA} < 30$ sec	amber	'beep'
AL 3	$t_{CPA} < 10$ sec	red	TRAFFIC



(a) Autonomy level 1 with the AMM, taxi route and CDTI.

(b) Autonomy level 2 with the additional alerting functions showing conflicts of AL 1 and AL 3.

Figure 6 Taxi display presented on the ND for autonomy levels 1 and 2

V. Experimental evaluation

A Goal of the experiment

The main goal of the experiment was to determine whether flight crews were able to taxi the aircraft and solve conflicts under autonomous conditions.

B. Subjects

Five crews of two professional male airline pilots participated in the experiment. Their ages ranged from 30 to 56 years ($\mu = 43.3$, $\sigma = 9.3$) and they had an average experience of 6,755 flight hours. Two subjects had (experimental) experience with taxi displays, five with datalink technology and four had used digital maps on an Electronic Flight Bag (EFB) before.

C. Independent variables

Two independent variables were used: the three autonomy levels as previously described and the following two visibility conditions, see Table 3:

- 400m RVR: flight crews should be able to perform CD&R by visual reference [3]; and
- 150m RVR: flight crews cannot perform CD&R but should be able to taxi based on the outside view.

D. Simulator setup

The National Aerospace Laboratory's (NLR) 6 DOF civil flight simulator GRACE (Figure 7) was used to conduct the experiment. The hardware and software of GRACE are configurable for research purposes and a Boeing B747 cockpit layout was used. Two EFB displays functioning as DCDUs were installed at both sides of the cockpit. Traffic was simulated by NLR's Traffic Manager (TMX).

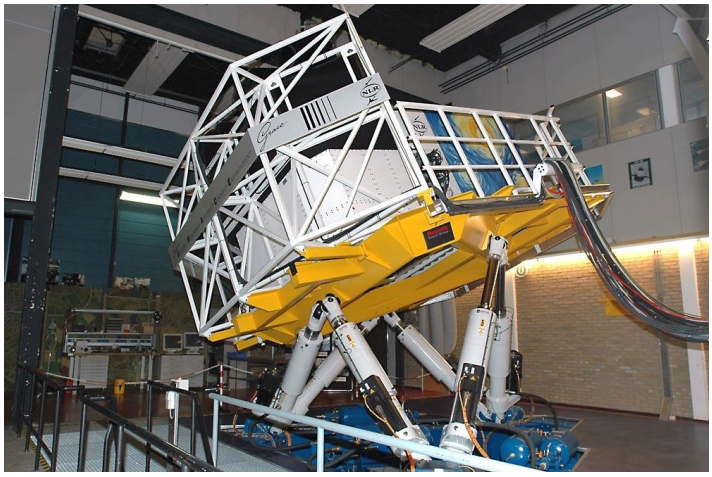


Figure 7 GRACE simulator at NLR

E. Procedures

Each flight crew participated in the experiment for one day, consisting of the following sessions: briefing, pre-experiment questionnaire, four simulator sessions of which the first served as a training session each containing after-run questionnaires, after-experiment questionnaire and a debriefing session. Each simulator session contained four scenarios, during which the role of PF and PNF was switched. The twelve experiment scenarios were performed in random order and the independent variables were varied as shown in Table 3.

Table 3 Experiment matrix

Cond.	Pilot flying	Autonomy level	Visibility condition
1	Captain	0	400m RVR
2	First Officer	0	400m RVR
3	Captain	1	400m RVR
4	First Officer	1	400m RVR
5	Captain	2	400m RVR
6	First Officer	2	400m RVR
7	Captain	0	150m RVR
8	First Officer	0	150m RVR
9	Captain	1	150m RVR
10	First Officer	1	150m RVR
11	Captain	2	150m RVR
12	First Officer	2	150m RVR

F. Scenarios

Each scenario consisted of an inbound or outbound taxi-run of approximately ten minutes at AAS. Before the start of the run the taxi route was uplinked and presented on both the DCDU (Figure 8) and the taxi display (Figure 6).

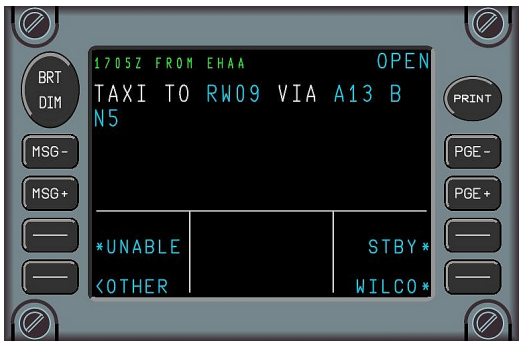


Figure 8 DCDU interface

Background traffic was present in all scenarios to increase the level of realism. In addition, each scenario contained intruding aircraft, to create a number of conflict events during the run. Conflicts varied (location and intruder), to avoid predictability. Three groups of comparable events that assumingly would require the same amount of workload were used: crossing traffic from the right, crossing traffic from the left, and traffic in front of the ownship slowing down.

After each run, subjects completed an after-run questionnaire, consisting of workload, SA, safety, and efficiency ratings. Workload was measured with the NASA-TLX scale [16] and SA with the Situational Awareness Rating Technique (SART) [17,18].
Subjects were instructed to complete each run by adhering to the taxi route provided and to control the aircraft like they would do in reality. The Rules of the Air [19] applied with respect to the right-of-way.

G. Measurements

Objective data collected consisted of the ownship performance data (aircraft parameters, display settings) and conflict data (ALs). Eye tracking software FaceLAB [20] was used to record the subject's point of gaze. Subjective data were collected by questionnaires.

VI. Results and discussion

The experiment held was the first study of the autonomous taxi concept, evaluating the safety, efficiency and acceptability with respect to CD&R.

A. Safety

1. Navigation errors

Navigation errors are defined as deviations from the assigned taxi route. In two runs (3,3%) a navigation error occurred, both during 150m RVR and autonomy level 1. One crew missed an assigned turn and taxied onto a wrong taxiway and another crew deviated from the centerline and ended up on the taxiway shoulders. Both mistakes were immediately identified and corrected.

The AMM was expected to contribute largely to the navigation performance of the flight crew [8], yet two serious errors occurred. Analysis indicated that the first mistake was due to miscommunication (the PNF provided wrong instructions to the PF). The second mistake occurred because both pilots were distracted by a conflict of two nearby aircraft on the AMM. This indicates that traffic situations concerning other aircraft may be distracting and possibly only a selection of relevant traffic should be presented to prevent this. Additionally route deviation alerting could be applied to warn the crew in time of the deviation.

2. Conflict anticipation

During the autonomy level 0 scenarios, conflict anticipation depended on ATC instructions. Therefore only conflict anticipation during the autonomy levels 1 and 2 can be considered, which implies that basically the impact of conflict alerting is examined. Out of 50 planned conflicts where the ownship had to give way, 43 actually occurred and were analysed in more detail with respect to reaction time, alert level and separation. Pilot response to determine reaction time was defined as a clear adjustment of the aircraft's ground speed by a decrease of thrust or use of the brake pedals.

Reaction time was measured referenced to the conflict start, therefore a negative reaction time implies anticipation before situation was defined as a conflict. Average reaction times were lower for scenarios with alerting, but no significant difference was found. Reaction time may however not be a good indication of conflict anticipation. The conflict start is determined using the state-vector and does not take the distance to the conflict (CPA) into account. Yet, this distance may be an important trigger for pilot reaction. Furthermore, the instance of reaction says nothing about the instance of detection. The conflict can mentally be solved before a response is given. In spite of this, Figure 9 shows that alerting contributes considerably to the reaction time. The number of responses is higher immediately after the alert is given when comparing autonomy level 2 with 1. This is a logical result, as subjects directly react to the alert. When the subjects know that alerting is enabled, this may also cause them to wait for an

alert before they take action. The automation (alerting) influences the behaviour of the flight crew [21].

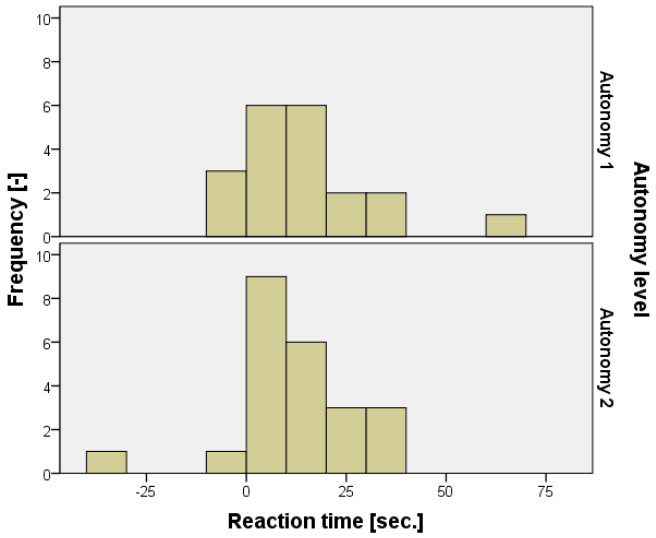


Figure 9 Reaction times frequency distributions.
Reaction time = 0 when alerts are given during autonomy level 2

The *Alert level* (AL) is derived from the remaining time to the conflict at the instance of reaction and indicates the severity of the conflict. Comparing the ALs at the moment of reaction does not give significant results, mainly due to the small dataset. Nevertheless as shown in Table 4, a difference between the autonomy levels exists. AL 3 never occurred during autonomy level 2. That AL 3 did occur during the autonomy level 1 condition may be caused by the pilots not experiencing the AL 3 situation as a direct threat. This could imply that the alerts were given too early. Of the subjects, 8 out of 10 however agreed to the alert timings being satisfactory and one found them too late.

*Table 4 Alert level at reaction * Autonomy level Crosstabulation*

	Autonomy level 1		Autonomy level 2		Total	
Alert level 0	2	(10.0%)	3	(13.0%)	5	(11.6%)
Alert level 1	6	(30.0%)	10	(43.5%)	16	(37.2%)
Alert level 2	8	(40.0%)	10	(43.5%)	18	(41.9%)
Alert level 3	4	(20.0%)	0	(0%)	4	(9.3%)
Total	20	(100.0%)	23	(100.0%)	43	(100.0%)

Separation distances at the instance of reaction are compared as a third indicator of the response of the pilot to the conflict severity. Figure 10 shows box plots of these separation distances for both independent variables. It shows that the separation distances were larger for autonomy

level 2 when compared to 1. This effect is largest for the 150m RVR condition. A Mann-Whitney test [22] confirms that the separation distance was significantly larger during autonomy level 2 ($U = 116.00$, $p < 0.01$, $r = -0.42$). For the 150m RVR visibility conditions the difference is highly significant ($U = 26.50$, $p < 0.001$, $r = -0.62$), while no significant difference is found for the 400m RVR condition ($U = 25.00$, ns, $r = -0.09$). The findings show that alerting indeed signals the pilot to take action. This causes lower alert levels to occur and larger separation distances to be kept. Overall, this results in safer situations for autonomy level 2.

3. Situational Awareness

SA was measured after each run with the SART-10D self-rating technique [17]. 115 Of the 120 SA questionnaires completed were valid. The average scores are presented in Figure 11. Factorial Analysis of Variance [22] (ANOVA) shows that the autonomy level has a significant main effect on the SA ($F(2,109) = 3.75$, $p < 0.05$, $\omega 2 = 0.04$). Post hoc tests revealed that the amount of SA is significantly higher for autonomy level 2 ($p < 0.05$) in comparison with autonomy level 0. Between other autonomy levels no significant differences were found. The SA scores were higher for the better visibility conditions, but this was a non-significant effect.

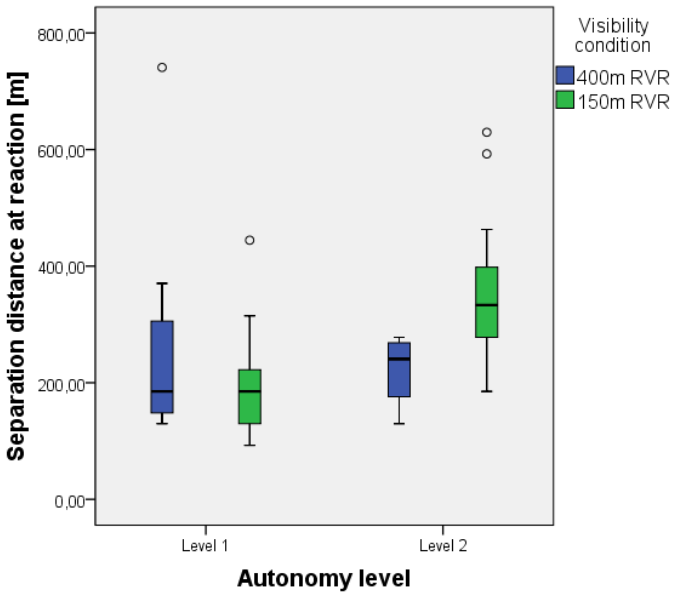


Figure 10 Separation distances for the different experiment conditions

Also no interaction effect between autonomy and visibility was found. This means that the visibility condition does not influence the amount of SA for the different autonomy levels. The increase of SA by autonomy level can be explained by the increased support. The 400m RVR condition should allow for CD&R using the outside vision, this did however not contribute to a significantly higher SA. Subjects found the additional support provided on the taxi display very clear. The CDTI created a visual picture of the surrounding traffic, said to add

to the SA. The missing ATC support however was said to decrease the SA during autonomy levels 1 and 2, due to the lack of R/T background information and consequently the missing information on other aircraft's intent.

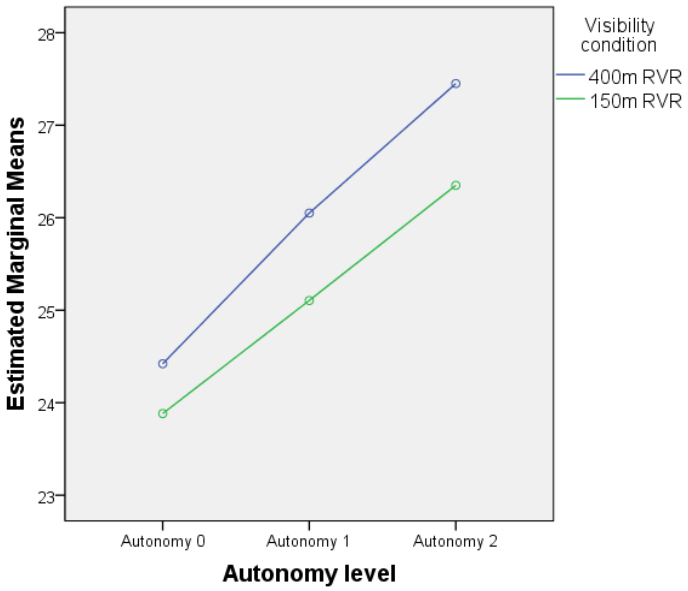
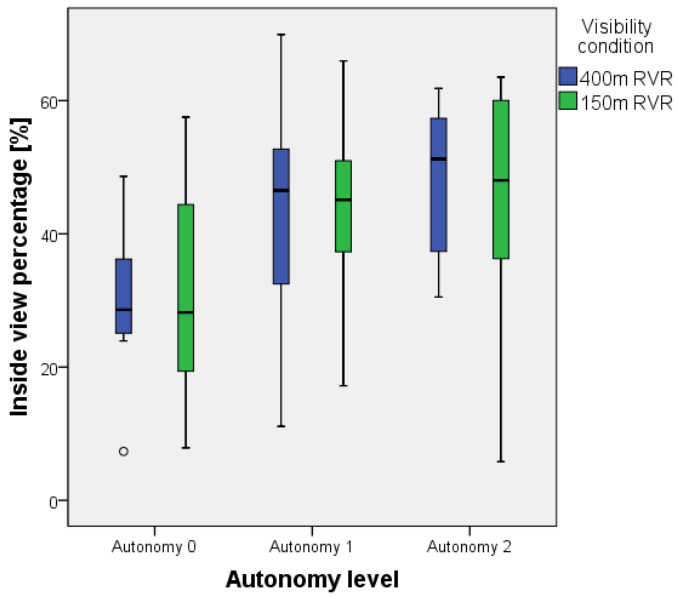


Figure 11 SART-10D average scores for the different experiment conditions

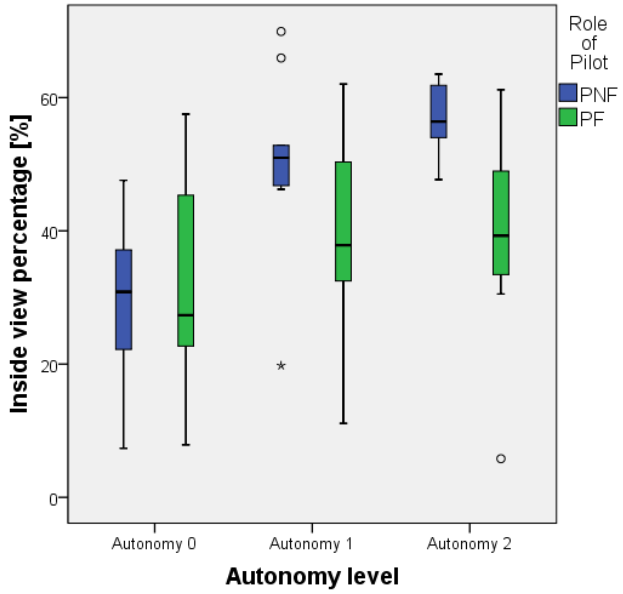
4. Head-down time

Head-down time was analysed using the tracked pilot gaze. Due to subjects looking outside the range of the eye trackers and system inaccuracies however, the data was incomplete and 46 data sets were excluded from the analysis. These invalid data sets were mostly subject dependent. The head-down time is expressed as a percentage of the total recorded pilot gaze time, as presented in Figure 12a. For the higher autonomy levels the amount of head-down time increases, which is confirmed as a significant main effect by a factorial ANOVA ($F(2,68) = 8.24$, $p < 0.01$, $\omega 2 = 0.09$). Post hoc test show a significant increase for both autonomy level 1 ($p<0.05$) and autonomy level 2 ($p<0.01$) with respect to autonomy level 0. For the visibility condition no main effect or interaction effect with the autonomy level was found. The findings indicate that the flight crew looks more inside the cockpit for CD&R during autonomy levels 1 and 2 and suggests more intensive use of the taxi display in those situations. No significant difference was found between both autonomous conditions. It was expected that the alerting function would reduce the need for constant monitoring of the taxi display but an increase of head-down time for autonomy level 2 is observed instead. This might be caused by the alerting triggering both pilots to look inside.

The head-down time of the PF and PNF is presented in Figure 12b. During autonomy level 0 both pilots look at the displays for a similar amount of time. During autonomy level 1 and 2 the head-down time of the PNF is much higher. This indicates a division of tasks, which was confirmed by the subjects. The PF focusses on controlling the aircraft, while the PNF monitors surrounding traffic and provides support.



(a) With respect to visibility condition.



(b) With respect to the role of the pilot.

Figure 12 Head down time error plots for the different autonomy levels

5. Subjective safety

After each run the subjects assessed the level of safety experienced on an ordinal scale from 1(very low) to 6 (very high). The results are shown in Figure 13, and indicate that the majority of runs were considered safe. The autonomy level 2 runs overall were rated safer than levels 0 and 1, and the better visibility condition was experienced as safer.

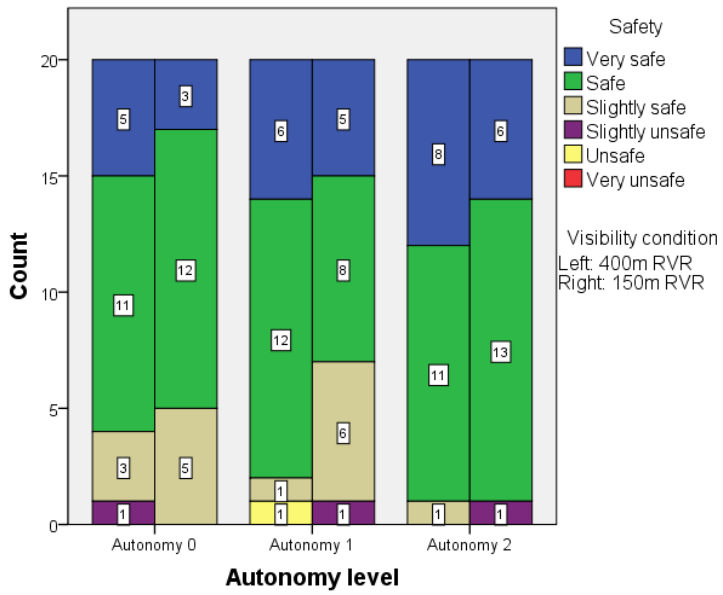


Figure 13 Subjective safety scores

During the autonomy level 0 most subjects noticed that safety completely depended on ATC. In particular during 150m RVR situations, ATC was the only source of traffic information. During the autonomous conditions the biggest issue was the missing intention information of other aircraft. This created a need to contact ATC, which was not possible. Overall the poor visibility was considered the biggest safety issue. Based on the subject's comments the differences in safety scores can be attributed to run-dependent situations rather than the independent variables.

B. Efficiency

1. Taxi speed

The average groundspeeds during taxiing are presented in Figure 14. They show opposite trends for both visibility conditions; taxi speeds increase at 400m RVR and decrease at 150m RVR. A factorial ANOVA confirms the visibility condition to be a significant main effect ($F(1,54) = 23.616$, $p < 0.001$, $\omega 2 = 0.15$) but not the autonomy level. A significant interaction effect is found ($F(2,68) = 6.059$, $p < 0.05$, $\omega 2 = 0.037$), which confirms that the visibility conditions of 400m RVR and 150m RVR are affected differently by the autonomy level.

The results found are however not confirmed when the taxi speeds are considered per crew. The limited amount of data however does not allow a detailed analysis. Furthermore, it is likely that scenario dependent events, like the amount of stops, have had a major impact on the taxi speeds. Therefore the validity of the trends found can not be confirmed.

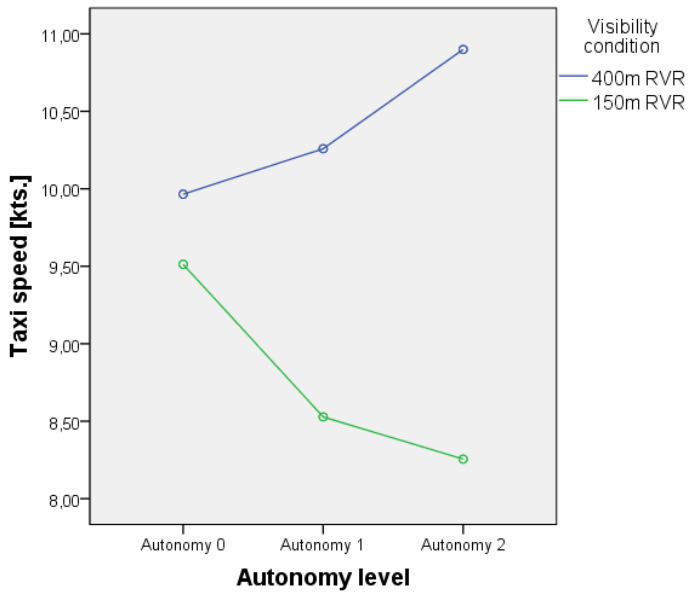


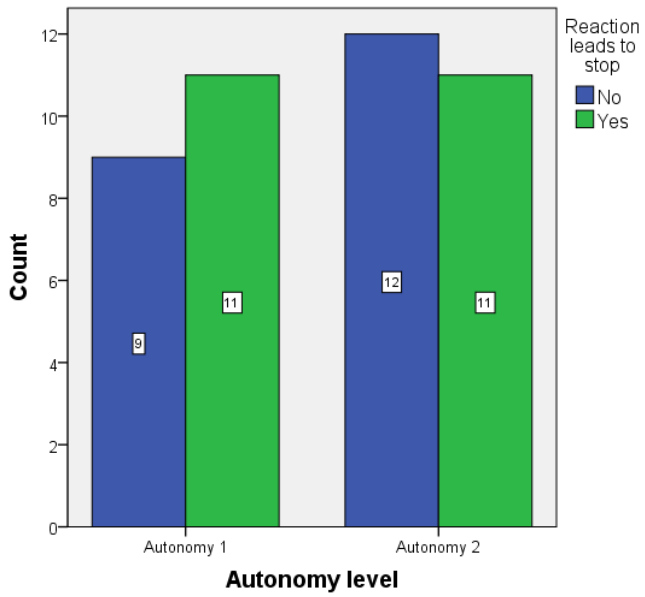
Figure 14 Taxi speeds for the for the different experiment conditions

2. Unforced stops

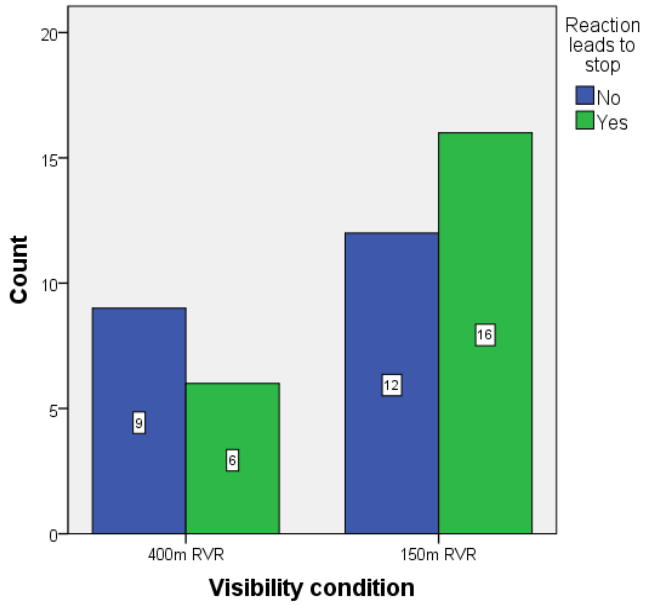
Unforced stops are examined as clearly inefficient situations. During taxiing, most power is needed to get the aircraft rolling; hence unnecessary stops are expensive events. When required, the efficient solution would be to anticipate by timely reducing speed.

Again the 43 conflict situations where the ownship had to give way were analysed. In 22 of these cases the ownship stopped and in 21 a speed reduction led to conflict resolution. Only a small difference in stopping v. not stopping for both autonomy conditions is found, see Figure 15a. This may be caused by the alerting functionality informing the flight crew at an earlier stage. During 150m RVR the majority of conflict situations led to a stop while at 400m RVR most conflicts were solved by speed reduction, see Figure 15b. This may be caused by the flight crew's inability to perform CD&R based on the outside view at 150m RVR.

When the ownship has right of way in a conflict, speed reduction or stopping should not be necessary. Yet, out of 25 right of way conflicts in 10 cases speed was reduced, leading to a full stop in 4 cases. As observed during the experiment and commented by all subjects, this was caused by the unclear intentions of other aircraft resulting in (overly) cautious behaviour to ensure safety. Despite of the order of priority being clear, 8 of the 10 subjects would like to have additional information on other aircraft's intention and route. This information could be provided, e.g.by visual cues on the taxi display, to further improve the efficiency of the concept.



(a) Stops vs. autonomy level



(b) Stops vs. visibility condition

Figure 15 Number of stops for situations where the ownship had to give right of way

3. Subjective efficiency

The subjects rated the efficiency on an ordinal scale from 1 (very low) to 6 (very high), as presented in Figure 16. Most runs were rated efficient, and differences between the various conditions are very small. Subjects commented that the taxi display contributed positively to the efficiency whereas the lack of ATC was said to be a negative factor.

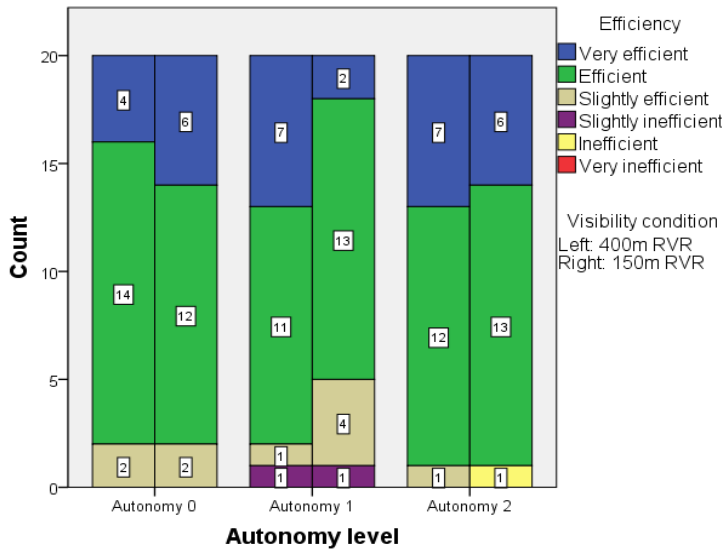


Figure 16 Subjective efficiency scores

C. Acceptability

1. Workload

The NASA-TLX workload scores showed that "Mental Demand" and "Effort" were the largest contributors to the workload experienced. Figure 17 presents the total workload for all different conditions, using normalized ($\mu = 0$, $\sigma = 1$) scores to discard inter-subject variability. It shows that for 150m RVR the measured workload is about the same while for 400m RVR the workload for autonomy levels 1 and 2 in particular seems lower. Visibility is confirmed to be a significant main effect by a factorial ANOVA ($F(1,114) = 7.483$, $p < 0.01$, $\omega 2 = 0.053$). Taxiing under low visibility is known to be a highly demanding task [9,10] and the results confirm that worsening visibility creates a higher workload. The impact of the visibility condition suppresses that of the autonomy. The decreasing workload for autonomy levels 1 and 2 at 400m RVR is found to be not significant.

2. Subjective acceptability

The subjects rated the acceptability on a scale from 1 (very unacceptable) to 6 (very acceptable), as shown in Figure 18. Overall, the 400m RVR condition was rated as more acceptable. Further reduction of visibility seems to make taxiing less acceptable. The scores for autonomy levels 0 and 2 are a bit higher than those for level 1. Subject's indicated that this was due to lack of safety (15% of the cases) and workload increase (12,5%) during autonomy level 1. Apparently, based on the higher scores for autonomy level 2, this is to some extent counterbalanced by the alerting functionality. The subjects who rated autonomy level 2 as unacceptable indicated safety (12,5%) and to a lesser extent workload (5%) to contribute to the unacceptability. Subjects regard ATC to be a crucial element during LVC. Its unavailability makes autonomy levels 1 and 2 less acceptable.

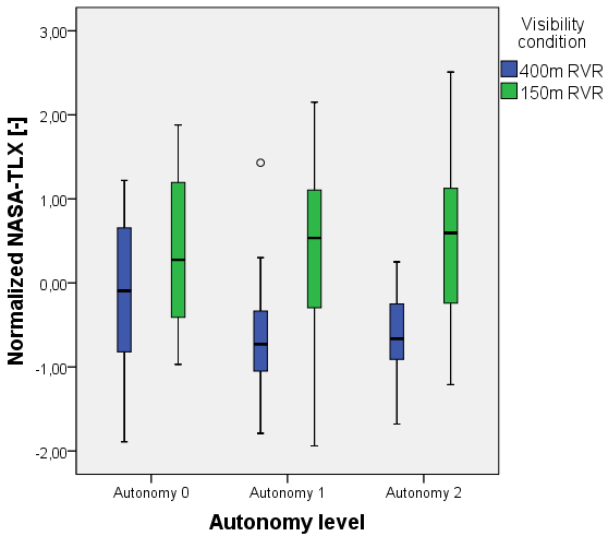


Figure 17 Normalized NASA-TLX scores

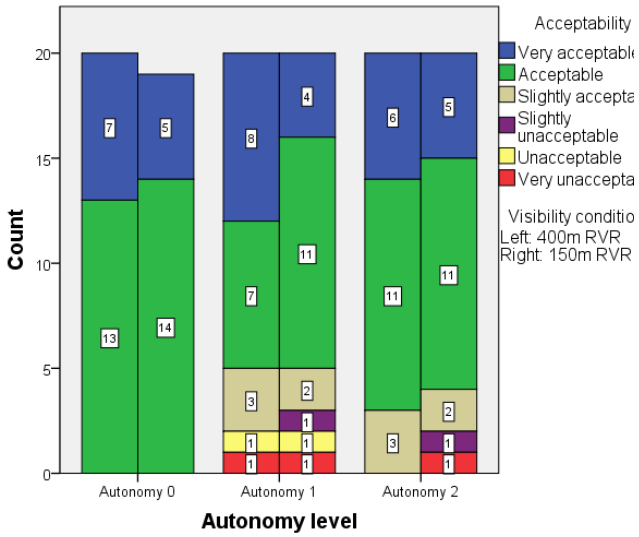


Figure 18 Subjective acceptability scores

VII. Conclusions and recommendations

The current study evaluated the full autonomous taxiing concept as a means to increase airport capacity during LVC. An experiment was conducted to evaluate the abilities of flight crews to taxi and perform CD&R. First results show that it is possible for flight crews to operate at the airport surface autonomously. The subjects were in all cases able to timely monitor and resolve potential conflicts without this being accompanied by a significant workload increase. The alerting function clearly had a positive influence on conflict anticipation.

The results are less satisfying when efficiency is considered. Therefore, the concept in its current application is not expected to improve airport ground capacity. The lack of information on other aircraft's intent is the main cause of this inefficiency (unnecessary speed reduction and stops). From the subject's point of view, ATC is essential, particularly during LVC. There was a high demand for ATC support and the lack of it made the autonomous taxi concept less safe and difficult to accept. The demand for ATC may however to some extent be replaced by provision of intent information as well.

The taxi display was seen as helpful support, improving navigation and SA and as such improving safety. Each level of the taxi display as evaluated was experienced as useful.

Further research of the full autonomous taxi concept should focus on the provision of intent information, which may have a positive effect on efficiency. In addition to CD&R as evaluated in the current study, more advanced topics like timing and sequencing need to be addressed. The current taxi display system has proven to be a solid basis for further developments.

Alternatively intermediate concepts of task division between flight crew and ATC could be considered, which can help lower controller workload.

Acknowledgments

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