Automation Concept for Cockpit Crew Integration into Trajectory-Based Dispatch Towing

Automatisierungskonzept zur Integration der Cockpitbesatzung in trajektorienbasierte operationelle Schleppverfahren

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Abstract

International hub airports are commonly the bottleneck of commercial airline flight operations. Social and political constraints often inhibit construction expansions of the surface infrastructure. Consequent airport congestion leads to increased taxi times, causing delays as well as additional fuel consumption and emissions. Surface trajectory-based operations (STBO), which are addressed by current research activities, reduce taxi times by introducing time or speed constraints along the taxi route. However, present-day aircraft are not equipped with technologies enabling the precise execution of predefined continuous speed profiles.

This thesis proposes a retro-fit concept named trajectory-based dispatch towing (TBDT), which allows present-day aircraft to execute STBO without extensive modifications. The concept suggests a further automated version of the novel towing vehicle TaxiBot as the enabling technology. Combined with an innovative cockpit application running on an electronic flight bag (EFB), the envisaged tractor shall support pilots of conventional aircraft to maneuver according to dynamic trajectories.

Following an analysis of conventional taxi operations, scenarios for the successive introduction of TBDT are developed. The consecutive steps focus on the integration of pilots into the designed taxi procedures. The aim of this research is to demonstrate the general feasibility of TBDT and to evaluate different automation modes from the perspective of the cockpit crew.

The iterative approach includes expert interviews and preliminary simulator trials. Qualitative feedback and quantitative measurements support the development of a prototypical human-machine interface (HMI) intended to run on an EFB. This graphical interface is supplemented by soft- and hardware implementations as well as an automatic control concept realized in the flight research simulator, D-AERO, at the Institute of Flight Systems and Automatic Control (FSR) of Technische Universität Darmstadt.

Based on this setup, 24 commercial airline pilots participated in the main simulator campaign. By means of a repeated measures design, every pilot completed one conventional taxi run and four TBDT operations. The TBDT runs differ with regard to automated or manual steering, braking, and their corresponding combinations. The trials investigate the interference of the automation modes and the aspects of performance, traffic awareness, user satisfaction, and acceptance of the pilots. The results of objective and subjective measurements indicate that all considered automation modes are generally suitable for executing TBDT. Furthermore, possible automation of the steering control has no significant effect on the measurements. On the contrary, the automation of brake input during TBDT results in enhanced performance and traffic awareness. The analysis of questionnaires shows a correlation between the expected safety benefit and the willingness of the pilots to hand over the speed control to an automated instance.

The evaluation results allow for both the detection of the feasibility of the concept as well as for the formulation of advice regarding the aspired amount of automation. The thesis is complemented by recommendations regarding future development and research activities.

Kurzfassung

Die Kapazitätsengstelle Flughafen lässt sich durch bauliche Erweiterungsmaßnahmen häufig nicht dynamisch an das steigende Flugverkehrsaufkommen anpassen. Bezüglich des Rollprozesses zwischen Flugsteig und Start- beziehungsweise Landebahn führt dies zu längeren Rollzeiten, Verspätungen und damit verbunden zu einem erhöhten Treibstoffverbrauch sowie zu zusätzlichen Emissionen. Ein Forschungsansatz, der eine Erhöhung der Vorhersehbarkeit sowie eine Verringerung der Rollzeiten adressiert, betrachtet die Einführung trajektorienbasierter Rollverfahren. Die Routenvorgaben der Vor- und Rollfeldkontrolle sollen dabei um eine zeitliche Komponente ergänzt werden. Die technische Ausrüstung heutiger Verkehrsflugzeugmuster bietet der Cockpitbesatzung jedoch keine Möglichkeit, kontinuierliche vordefinierte Geschwindigkeitsprofile präzise umzusetzen.

Die vorliegende Dissertation betrachtet in diesem Kontext einen innovativen Ansatz, der es konventionellen Flugzeugen ermöglicht, vordefinierten Geschwindigkeitsprofilen zu folgen und somit entsprechend definierte Rolltrajektorien umzusetzen. Als Schlüsseltechnologie wird dabei ein automatisierter Schlepper, der eine Weiterentwicklung der aktuell erprobten TaxiBot-Technologie darstellt, vorgeschlagen. Dieser ermöglicht in Kombination mit einem unterstützenden Anzeigesystem, das auf einem Electronic Flight Bag (EFB) realisiert wird, die Integration aktueller Flugzeugmuster in ein trajektorienbasiertes Rollsystem ohne zusätzliche Modifikationen.

Aufbauend auf einer Prozessanalyse, die die Anforderungen der vielseitigen Teilhaber des Rollprozesses berücksichtigt, wird eine Szenariobeschreibung zur Einführung trajektorienbasierter operationeller Schleppverfahren entwickelt. Hinsichtlich der weiteren Untersuchung, die den Fokus auf die Integration der Pilotinnen und Piloten legt, werden unterschiedliche Automatisierungsgrade bezüglich der Cockpitprozesse definiert. Ziel der Studie ist der Nachweis der generellen Machbarkeit sowie die Bewertung der Automatisierungsgrade aus Cockpitsicht.

Mittels strukturierter Experteninterviews und einer Vorversuchskampagne wird ein prototypisches Anzeigeformat zur Verwendung auf einem EFB entwickelt. In Kombination mit der soft- und hardwareseitigen sowie der regelungstechnischen Implementierung in den Forschungsflugsimulator D-AERO des Instituts für Flugsysteme und Regelungstechnik der Technischen Universität Darmstadt bildet das entwickelte Anzeigesystem die Grundlage für die abschließende Versuchskampagne.

Die Hauptuntersuchung umfasst eine Simulatorkampagne mit 24 Verkehrspiloten der kommerziellen Luftfahrt. Neben der Simulation des konventionellen Rollvorgangs werden jeweils vier Umsetzungen des trajektorienbasierten Konzepts, die sich in der Automatisierung der Lenk- und Bremseingaben unterscheiden, betrachtet. Objektive und subjektive Messverfahren dienen der Beantwortung der Fragestellung, wie sich die Variation der Automatisierungsgrade auf die Performanz, das Verkehrsbewusstsein, die Gebrauchstauglichkeit sowie die Akzeptanz der Pilotinnen und Piloten auswirkt. Die Ergebnisse der Simulatorstudie zeigen, dass sich unter den gegebenen Randbedingungen alle betrachteten Umsetzungen zur Realisierung trajektorienbasierter Rollprozesse eignen. Zudem zeichnet sich kein Indiz ab, dass die Automatisierung der Lenkung Vorteile bezüglich der zuvor genannten Messgrößen bietet. Bezogen auf die Bremseingaben lässt sich feststellen, dass automatisierte im Vergleich zu manuellen Bremsungen Vorteile hinsichtlich Performanz und Verkehrsbewusstsein bieten. Des Weiteren zeigt sich, dass die Bereitschaft der Piloten, die Geschwindigkeitsregelung vollständig an die Automatisierung zu übergeben, mit dem erwarteten Sicherheitsgewinn korreliert.

Neben der Feststellung der cockpitseitigen Machbarkeit trajektorienbasierter operationeller Schleppverfahren ermöglichen die Untersuchungsergebnisse die Formulierung von Handlungsempfehlungen hinsichtlich des Umfangs der Automatisierung. Abschließend werden weiterführende Modifikationen des Anzeige- und Schleppkonzepts sowie zukünftige Forschungsansätze vorgeschlagen.

Danksagung

Die vorliegende Dissertation ist während meiner Tätigkeit als wissenschaftlicher Mitarbeiter am Institut für Flugsysteme und Regelungstechnik (FSR) der Technischen Universität Darmstadt entstanden. Spannende Projekt- und Lehraufgaben ermöglichten es mir, vielfältige Aspekte der Flugsystemtechnik zu bearbeiten, sowie die hier präsentierte Forschung durchzuführen. Daher danke ich zunächst Professor Dr.-Ing. Uwe Klingauf, der mir als Institutsleiter diese Möglichkeit geboten hat und mich durch seine Betreuung in den letzten Jahren in der Entstehung dieser Dissertation unterstützt hat. Zudem danke ich Professor Dr.-Ing. Peter Hecker des Instituts für Flugführung der Technischen Universität Braunschweig für die Übernahme des Korreferats und die kritische Auseinandersetzung mit meinem Thema.

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Abschließend bedanke ich mich bei Freunden und Familie. Insbesondere meiner Frau Jennifer Bernatzky danke ich für die unermüdliche Unterstützung in allen Phasen der Promotion und darüber hinaus.

Darmstadt, Juni 2019 *Torben Bernatzky*

Contents

Symbols and Abbreviations

Variables

Symbol	Unit	Description
a	$^{m}/_{s^2}$	Acceleration
a	—	Questionnaire score
$\widetilde{a}$	—	Transformed questionnaire score
d	m	Distance
F	N	Acceleration and deceleration force
F	—	Test statistic of analysis of variance (ANOVA)
GS	$^{m}/_{s}$	Aircraft ground speed
lat, lon	rad, rad	Nose wheel position
n	—	Number (of participants)
p	—	Probability
r	—	Correlation coefficient
s	m	Arc length along planned trajectory
t	s	Time
$\widetilde{t}$	—	Transformed time
z	—	Test statistic of Wilcoxon signed-rank test
Ψ	rad	Aircraft heading
Φ	rad	Steering angle
κ	$^{1}/_{m}$	Trajectory curvature
χ^2	—	Test statistic of Friedman's ANOVA
Δa	$^{m}/_{s^2}$	Difference between actual and target acceleration
ΔGS	$^{m}/_{s}$	Difference between actual and target ground speed
$\Delta pedal$	rad	Difference between actual and target pedal deflection
Δs	m	Position error (arc length along planned trajectory)
Δt	s	Difference between times
$\Delta\Psi$	rad	Difference between actual and target aircraft heading

Subscripts and Superscripts

Subscript	Description
BRK	Applied by aircraft brakes
CPT	Captain
$crit$	Critical
FO	First officer
fw	Feed forward
MB	During manual brake phases
max	Maximum value
min	Minimum value
$noMB$	Beyond manual brake phases
p	Planned value on trajectory position closest to actual nose wheel position
r	Reaction (time)
S	Spearman's (correlation)
SFO	Senior first officer
SW	Shapiro-Wilk test
t	Planned value at actual time step
tr	Applied by/via tractor
trg	Target value
$turn$	During turns
$\perp$	Perpendicular regarding trajectory segment closest to actual nose wheel position
25	25^{th} percentile
75	75^{th} percentile

Superscript	Description
$+$	Positive values

Mathematical Notation

Notation	Description
M	Mean value of sample
max	Maximum of sample
min	Minimum of sample
SD	Standard deviation of sample

Abbreviations

4D-SMAN	trajectory-based surface manager
A-CDM	Airport Collaborative Decision Making
AMDB	aerodrome mapping database
AMM	airport moving map
ANOVA	analysis of variance
ANS	air navigation service
ANSP	air navigation service provider
APU	auxiliary power unit
A-SMGCS	Advanced Surface Movement Guidance and Control System
ATC	air traffic control
ATCO	air traffic controler
ATM	air traffic management
CDM	Collaborative Decision Making
CI	confidence interval
ConOps	concept of operations
CTOT	calculated take-off time
DLR	German Aerospace Center
CPDLC	controller-pilot data link communications
EASA	European Aviation Safety Agency
EFB	electronic flight bag
EGTS	Electric Green Taxi System
EIBT	estimated in-block time
EXIT	estimated taxi-in time
EXOT	estimated taxi-out time
FAA	Federal Aviation Administration
FARGO	Flightdeck Automation for Reliable Ground Operation
FSR	Institute of Flight Systems and Automatic Control
HMI	human-machine interface
HUD	head-up display
ICAO	International Civil Aviation Organization
IFR	instrument flight rules
MABA-MABA	men are better at / machines are better at

NASA	National Aeronautics and Space Administration
ND	navigation display
NextGen	Next Generation Air Transportation System
NMOC	Network Manager Operations Center
OANS	On-Board Airport Navigation System
PFD	primary flight display
RBTO	route-based taxi operations
RTA	required time of arrival
RTLX	Raw Task Load Index
RTT	ramp transit time
SART	Situation Awareness Rating Technique
S-CDM	Surface Collaborative Decision Making
SESAR	Single European Sky ATM Research
SETO	single-engine taxi out
STBO	surface trajectory-based operations
SUS	System Usability Scale
TBO	trajectory-based operations
TBDT	trajectory-based dispatch towing
TBTO	trajectory-based taxi operations
TLX	Task Load Index
TND	taxi navigation display
TPBT	target push-back time
TSAT	target start-up approval time
TTOT	target take-off time

1 Introduction

Although the absolute duration of the taxi phase of a commercial aircraft is short compared to the remaining flight phases, unplanned additional taxi times have a noteworthy impact on flight delays. A joint study of the Federal Aviation Administration (FAA) and EUROCONTROL reveals that the additional taxi-out times of the largest 34 airports in the USA and Europe, visualized in Figure 1.1, have stagnated since 2011 [EF16, p. 58]. Comparing the mean additional with the mean absolute taxi times shows that the excess time accounts for about 45 % of the mean taxi time at Frankfurt Airport in 2013 [EF16, p. 58; EUR13, p. 1]. A major source of additional taxi time is the interaction between aircraft. For instance, at John F. Kennedy Airport, mean taxi-out times increase by a factor of 3.5 when the airport is congested [SB10].

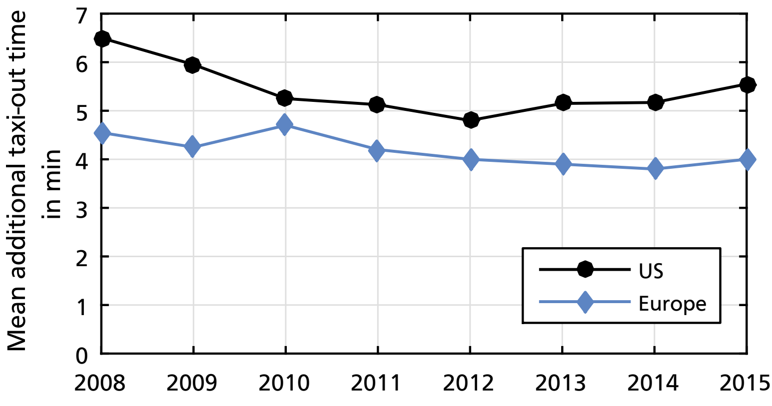


Figure 1.1.: Evolution of additional taxi-out time at the 34 largest airports in the USA and in Europe (illustrated by the author with data from [EF16, p. 58])

Besides the influence of taxi delays on punctuality, longer taxi times cause a significant amount of additional fuel burn. Deonandan and Balakrishnan investigate the potential of strategies for reducing taxi-out emissions and conclude that by eliminating all taxi delays caused by queues and congestion for the largest 20

US-American airports, fuel savings between 28 % and 60 % of the taxi fuel consumption can be reached [DB10, p. 13]. Kesgin further calculates that with conventional taxi technologies, emissions decrease by 6 % if taxi times decrease by 2 min [Kes06, p. 377]. Moreover, noise measurements reveal that idling engines produce a significant amount of airport noise affecting passengers, workers, and residents [HB16].

While congestion on ground is already a relevant factor for aircraft delays today, forecasts predict that the amount of European flights conducted by instrument flight rules (IFR) will increase by 17 % between 2017 and 2024 [EUR18b, p. ii]. For the same time period, the FAA estimates growth rates of 11 % for domestic and international departures in a baseline scenario for the United States [Fed18, p. 60]. As construction expansions of airports are often infeasible or protracted, further efforts for optimizing the taxi procedures are needed in order to deal with the growing demand. Concurrently, the European Commission outlines its vision of the future aviation system in the report *Flightpath 2050* and sets challenging goals regarding reduction of exhaust gas and noise emissions [Eur11].

An approach addressing the optimization of the flight mission considers the introduction of trajectory-based operations (TBO) as proposed by the International Civil Aviation Organization (ICAO) [Int16a]. The concept of TBO, which is further specified by the regional programs Single European Sky ATM Research (SESAR) (Europe) [SES15] and the Next Generation Air Transportation System (NextGen) (USA) [Nex11], proposes the introduction of 4-dimensional flight specifications with time being an additional constraint. Besides further enhancements, such as the implementation of seamless routes and altitude profiles as well as free-flight operations in suitable areas, the integration of time constraints into the flight plan and its execution shall result in a higher degree of predictability [SES15; Nex11]. As the first time constraint of the flight phase equals the final step of the taxi procedure, precisely planned and executed taxi operations are essential for the success of TBO. Thus, the SESAR Joint Undertaking requests the "full integration of airports" [SES15, p. 35] and ICAO as well as the NextGen Joint Planning and Development Office explicitly propose the implementation of surface trajectory-based operations (STBO) [Int16d, pp. 95-98; Nex11, p. 2-17]. Whilst conventional surface operations are route-based, meaning the controllers provide a target route without time or speed descriptions, STBO imply the generation of conflict-free route-descriptions with time or speed constraints. Thus, STBO offer a great potential for optimizing the surface traffic with regard to more predictable taxi operations, which supports the implementation of the SESAR and NextGen objectives [HCF14].

While it is probable that future aircraft generations or modified conventional aircraft will be further automated and thus may be suitable for the automatic execution of surface trajectories [Oku+16], current aircraft do not provide any support systems to execute predefined trajectories while taxiing.

1.1 Aim of this Thesis

There are two primary use cases for enabling present-day aircraft to follow trajectories. In a short-term scenario, a limited number of retrofitted aircraft allows for a risk-free, initial operational evaluation of STBO. In a longer-term scenario, homogeneous capabilities of all taxiing aircraft to follow trajectories need to be reached in order to fully benefit from the advantages of STBO. Even though next aircraft generations may be equipped with forward-fit, on-board automation for taxiing, the traffic mix will still include present-day aircraft. Accordingly, a retrofit solution for these remaining conventional taxiing aircraft can enable the complete implementation of STBO.

This study describes and investigates an innovative concept for implementing STBO enabled by automated tractors towing the aircraft from gate to runway and vice-versa. The study proposes an automated version of the existing dispatch towing technology TaxiBot. TaxiBot is a state of the art tractor which – after push-back – stays connected to the aircraft and can be fully controlled from the aircraft cockpit. Developed for the purpose of fuel efficient engine-less taxiing, an enhanced version of this technology can additionally serve as the enabling technology for the automated execution of STBO. The proposed implementation of an automated tractor towing the aircraft along a given route and speed profile is in the following referred to as trajectory-based dispatch towing (TBDT). This retrofit solution shall be supplemented by a human-machine interface (HMI) running on an electronic flight bag (EFB) providing information and guidance to the pilot. While the tractor is intended to be responsible for automated acceleration and slight deceleration of the aircraft-tractor combination, different automation modes regarding steering and braking are conceivable.

The purpose of this thesis is to define and investigate the concept of TBDT as well as to gain a deeper understanding of the pilot's role in this process. Correspondingly, this research focuses on the general applicability of TBDT, the developed cockpit HMI, and the suitability of different automation modes.

1.2 Structure of this Thesis

Supplementing the table of contents, Figure 1.2 illustrates the structure of this thesis by highlighting the conclusion of each chapter leading to the consecutive content.

Chapter 1 describes present-day taxi operations at international airports. Besides operational aspects, technologies supporting the stakeholders during taxiing are presented. Deriving the current and future challenges of surface operations leads to the demand for new methods like STBO.

Whilst the first chapter focuses on the state of the art, the second chapter deals with research activities regarding planning, optimization and execution of taxi trajectories. **Chapter 2** further includes general considerations for the design process of automated systems. Taking into account the challenges presented in the first chapter and current efforts in research, this chapter concludes with the description of the research gap, the formualtion of a global hypothesis, and the motivation for investigating TBDT.

The concept, which consists of an operational description and the definition of an HMI and a trajectory control architecture, builds upon identified requirements and constitutes the content of **Chapter 3**. Four specific hypotheses regarding the upcoming investigation complete this chapter.

The hypotheses are investigated and tested by means of a simulator study. **Chapter 4** lays the foundation for this study by defining the implementation into a flight research simulator and presenting the evaluation procedure.

The results of the study are summarized and discussed in **Chapter 5**. On the basis of the tested hypotheses, a concept assessment reflects the outcome by comparing it with the previously identified research gap and motivation for TBDT.

The conclusion and outlook in **Chapter 6** complement the thesis by summarizing and reflecting the outcome as well as by outlining future research demand.

1.3 Taxi Procedures and Technologies

As part of the gate-to-gate process, the taxi phase comprises the "movement of an aircraft on the surface of an aerodrome under its own power, excluding take-off and landing" [Int05, p. 1-5]. Correspondingly, the following explanations primarily deal with the process beginning after push-back and ending before entering the runway for outbound flights as well as between exiting the runway and arriving at the gate for inbound flights.

This section starts with a brief overview of the responsibilities of the control instances and the corresponding cockpit procedures. The operational circumstances

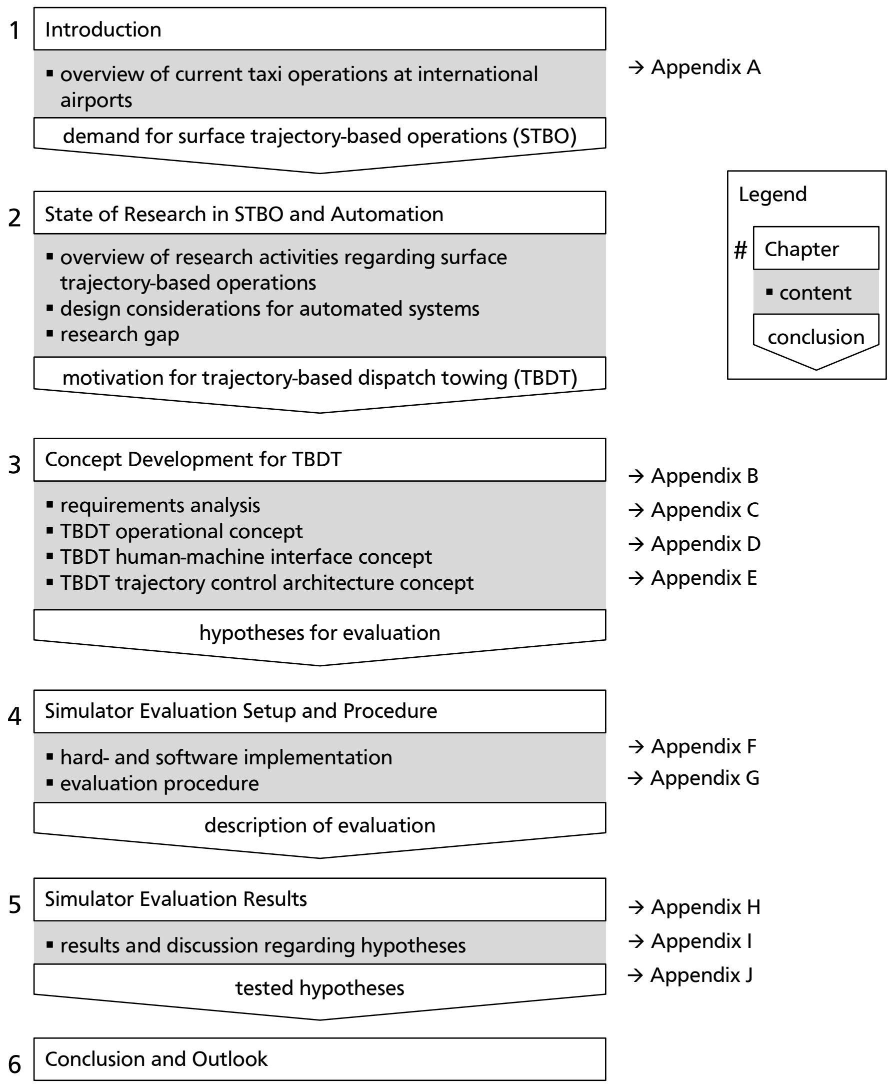


Figure 1.2.: Structure of this thesis

are followed by technical developments such as alternative taxi technologies and on-board tools supporting the pilots during taxiing.

The following explanations will focus on European procedures and nomenclature. Relevant differences with the US-American system will be pointed out if relevant.

1.3.1 Control Instances

In Annex 14 to the Convention on International Civil Aviation, ICAO defines the following airport areas used by aircraft:

> **Apron:** "A defined area, on a land aerodrome, intended to accommodate aircraft for purposes of loading or unloading passengers, mail or cargo, fueling, parking or maintenance." [Int16b, p. 11]
>
> **Maneuvering area:** "That part of an aerodrome to be used for the take-off, landing and taxiing of aircraft, excluding aprons." [Int16b, p. 14]
>
> **Movement area:** "That part of an aerodrome to be used for the take-off, landing and taxiing of aircraft, consisting of the maneuvering area and the apron(s)." [Int16b, p. 14]

The definition of the European Aviation Safety Agency (EASA) matches with the ICAO guideline. It needs to be noted that on several European airports the apron is not limited to loading and unloading operations [Eur14b]. At Frankfurt Airport for instance, several taxiways are located on the apron allowing for a seamless transition between maneuvering area and apron [Fra18].

On US-American airports the definitions differ, as the movement area borders with a non-movement area [Fed12]. The apron (also called ramp) is mostly located inside the non-movement area. Transitions between apron and maneuvering area are realized by designated spots located inside the non-movement areas connected to taxiways of the movement area [Fed12].

Although the specific implementation of the airport areas depends on the individual airport design, main responsibilities are regulated in a uniform manner. The maneuvering area (movement area in the USA) is controlled by air traffic control (ATC) while the apron (non-movement area in the USA) can be controlled by either ATC, airport operator, airline operator, or third party [Fed12; Eur13]. ICAO describes the procedures for aerodrome control services in Doc 4444 [Int16c]. Typical working positions of an aerodrome control tower are an aerodrome controller, a ground controller and a clearance delivery position [Int16c]. Pilots need to communicate with the ground controller when taxiing on the maneuvering area without crossing runways, while they have to call apron control when taxiing on the apron. The area definitions of ICAO and the corresponding control instances are visualized in Figure 1.3.

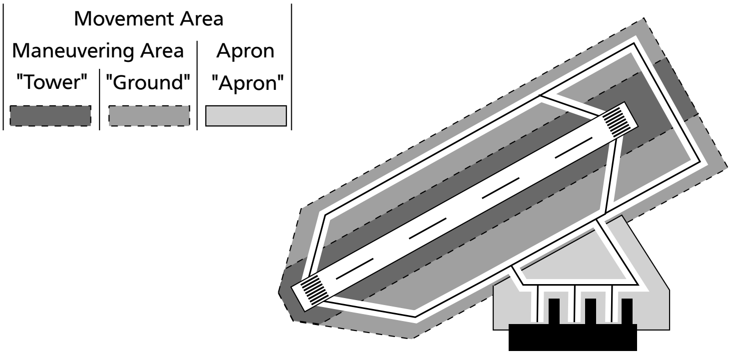


Figure 1.3.: Exemplary visualization of airport areas and responsible control instances defined in ICAO Doc 444 [Int16c]

During taxiing, the apron or ground controllers typically provide the target routes and designated holding points via radio communication. Depending on the airport and aircraft equipment, start-up or push-back clearances are alternatively transmitted via controller-pilot data link communications (CPDLC). The CPDLC message can also contain a description of the planned taxi route. Regardless of the transmission mode, controllers are responsible for assigning safe and efficient taxi routes and for providing clearances to the pilots.

1.3.2 Cockpit Procedures

In the cockpit, the pilot monitoring is commonly responsible for communication with the controllers. All received clearances need to be confirmed via either radio communication or CPDLC. The execution of taxi movements is carried out by the pilot taxiing.

Most medium- and long-haul aircraft are steered via a nose wheel steering wheel (also called tiller) inside the cockpit. Depending on the type and the individual configuration, some aircraft are equipped with only one steering wheel at the captain's position (e.g. [The08]). Most modern aircraft are equipped with an additional steering wheel at the first officer's position (e.g. [Air11; The07]) and airbus even advises that the pilot flying (who can also be the first officer) shall be in charge for taxiing on ground [Air08]. Nevertheless, several airlines only allow their captains to steer on ground.[1] In addition to steering via tiller, pilots can obtain nose wheel deflections to a given amount with the pedals. Furthermore, shallow turns can be realized via differential braking or differential thrust [Air01]. Regarding the velocity, the pilot taxiing controls the desired taxi speed manually. As no general speed limits for taxiing exist, airlines provide target and maximum speeds individually. As a reference, ICAO proposes common taxi speeds of 30 kn ($15.4\,\frac{\mathrm{m}}{\mathrm{s}}$) at straight taxiway segments and 10 kn ($5.1\,\frac{\mathrm{m}}{\mathrm{s}}$) on curves and on complex taxiway systems [Int04, p. 3-15].

Although airline cockpit operations are highly scripted, Loukopoulos, Dismukes, and Barshi observed high discrepancies between written materials and actual line operations [LDB03]. By means of a task analysis, the authors identified three main reasons for the difference between trained and actual procedures: real operations are not linear but contain several concurrent tasks, pilots do not have the full authority of the execution of procedural steps, and crews are frequently interrupted [LDB03].

1.3.3 Airport Collaborative Decision Making

The efficiency and predictability of the ground phase do not only depend on the taxi phase but also on all further instances responsible for offloading, preparing and loading the aircraft. According to the definition of the turnaround time (also called turn-round time) provided by EUROCONTROL, the turnaround comprises all processes between in- and off-block [EUR12]. As visualized in Figure 1.4, turnaround delays amount for more than one third of the departure delays on European airports. With 7 %, airport air navigation service (ANS)-related delays are responsible for a small but still relevant share of the total departure delays in 2016 [EUR17, p. 6].

The issue of delays caused by the turnaround is addressed by the European Union initiating Airport Collaborative Decision Making (A-CDM). A collaborative approach based on information sharing between all stakeholders shall harmonize the offloading, preparing, and loading of the aircraft [EUR12]. Moreover, the integration of the ANS providers shall ensure a seamless transition between gate,

[1] The majority of all study participants regarding this thesis stated that their company rules only allow the captain to control the aircraft on ground.

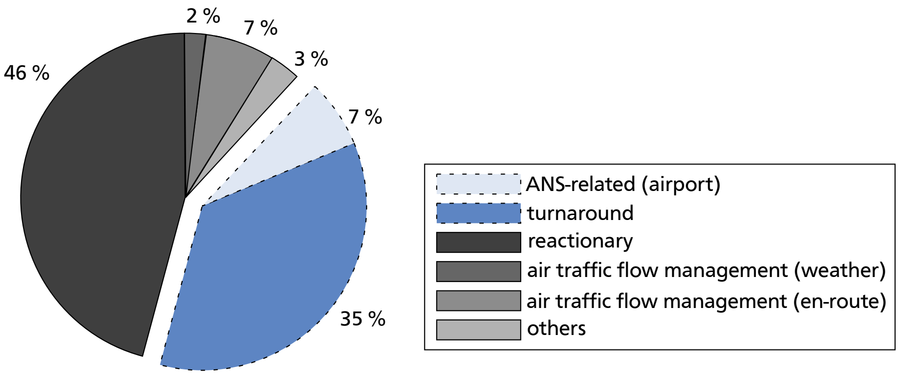


Figure 1.4.: Causes of departure delay at European airports in 2016 (illustrated by the author with data from [EUR17, p. 6])

taxi, and runway scheduling [EUR09]. EUROCONTROL defines the following six concept elements which airports need to consider for A-CDM implementation:

1. **Information sharing** between all stakeholders regarding the turnaround is essential for the implementation of A-CDM [EUR12].
2. **Milestone approach** ensures that all stakeholders have a common situation awareness regarding the progress of the turnaround [EUR12].
3. **Variable taxi times** build the link between gate processes and runway scheduling, enhancing the punctuality of take-offs [EUR12].
4. **Collaborative pre-departure sequence** allows for a sequencing of the off-block times at the gates [EUR12].
5. **Adverse conditions** during periods of capacity reductions can be handled by A-CDM in order to maintain collaboration [EUR12].
6. **Collaborative management of flight updates** is responsible for the information exchange between arrival and departure [EUR12].

Although A-CDM mainly focuses on the turnaround process at the gate, the milestone approach ensures a direct link to the flight and taxi phases by defining several estimated and target time steps. For a complete overview of the timeline,

Appendix A summarizes the characteristic times and the corresponding data exchange with the Network Manager Operations Center (NMOC) by the example of Frankfurt Airport. An excerpt of the diagram is shown in Figure 1.5 focusing on the time steps considered in A-CDM during the ground phase of the aircraft.

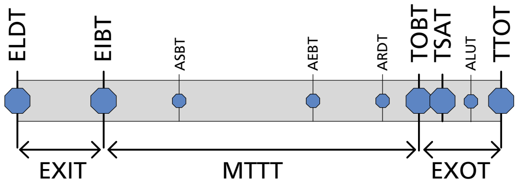


Figure 1.5.: Relevant time steps of A-CDM during the ground phase of the aircraft (illustrated by the author on the basis of the procedure description in [Air12], for abbreviations not mentioned in text refer to Appendix A)

The visualization demonstrates the importance of the variable taxi times namely estimated taxi-in time (EXIT) and estimated taxi-out time (EXOT) for the A-CDM target times target start-up approval time (TSAT) and target take-off time (TTOT). Accordingly, precise variable estimated taxi times are essential for the accuracy of the whole A-CDM process. Regarding the delays displayed in Figure 1.4, the punctuality of the turnaround is directly linked to the airport ANS performance.

At US-American airports the corresponding approach is called Surface Collaborative Decision Making (S-CDM) which is also based on information sharing [Fed12]. Sparenberg compares the European with the US-American Collaborative Decision Making (CDM) system, concluding that the departure management is handled differently. While in A-CDM target times like the TSAT serve as time constraints, in S-CDM a reactive departure management allows for a higher degree of freedom for the airlines and is still based on a "first come, first serve" principle [Spa16, p. 64]. Instead of defining EXIT and EXOT for the whole taxi phase, S-CDM distinguishes between ramp transit time (RTT) and a consecutive taxi time on the movement area [Fed12].

Although the CDM concepts define estimated taxi times differently, both consider static variable taxi times provided by look-up-tables, taking into account historical data, flight specific data, and expertise [Spa16].[2] Both CDM approaches do not consider interaction between taxiing aircraft [EUR12; Fed12].

2 In the case of A-CDM, the look-up tables further consider the airport conditions and simulation results [Spa16].

1.3.4 Advanced Surface Movement Guidance and Control System

The Advanced Surface Movement Guidance and Control System (A-SMGCS) is defined as "a system that supports surface movement operations in all weather conditions at an aerodrome based on defined operational procedures" [EUR18a, p. 12]. Initially specified by ICAO, the most important objective of the modular system is the assurance of spacing between aircraft even under low visibility [Int04]. Depending on the airport layout and individual demand, the following functions can be implemented [Int04]:

- surveillance,
- routing,
- guidance, and
- control.

While the latter functions are optional, *surveillance* is a mandatory component [EUR10]. Based on the detection of the airport infrastructure as well as of all mobiles and obstacles on the movement area, the *surveillance* function provides the controllers with a visual picture of the current traffic situation. Moreover, accurate times such as the actual landing time can be automatically sent to an A-CDM system [EUR18a]. Further input for A-CDM like the TTOT or the estimated in-block time (EIBT) is provided by the *routing* function which generates routes for every aircraft based on "known aerodrome parameters and constraints" [EUR18a, p. 36]. These planned routes can be presented to the controllers with additional distinction between cleared and pending segments [EUR18b]. The *guidance* function can only be implemented if *routing* is available and allows for off-board guidance aids like switchable taxiway center lines,[3] switchable stop bars, and visual docking guidance systems for precise parking positioning [Int04]. EUROCONTROL uses the term *airport safety services* instead of *control*, as this function provides support like runway monitoring and conflict alerting to the controllers, but does not include the controller working position itself [EUR18a].

Thus, the full implementation of A-SMGCS can contribute to higher predictability of taxi operations and enhanced performance. Nevertheless, the *routing* and *guidance* functions do not provide time or velocity constraints to the taxiing aircraft. Consequently, the actual taxi times still depend on individual pilot decisions and can only be predicted to a limited quality.

[3] Dynamically switchable taxiway center lights indicating the individual clearances and routes are also known as follow-the-greens which is available on several airports like London Heathrow or Singapore Changi [Hau+11].

1.3.5 Alternative Taxi Technologies

Common commercial medium- and long-haul aircraft taxi on ground with engine thrust. Procedures defined by airports and airlines limit the use of engines to forward thrust generation. Hence, the push-back as well as maintenance movements of empty aircraft are realized by tractors, while the forward taxi operations from gate to runway and vice versa are generally realized by engine thrust. During taxiing, the engines are mostly operated on idle leading to incomplete combustion which generates higher CO emissions [Sch+07]. In addition to this, engines are designed to obtain best specific fuel consumption at common cruise speeds and altitudes. When taxiing on ground, fuel efficiency decreases significantly [JHT15]. Fuel efficiency is even lower when pilots apply the brakes in order to reduce speed or to follow stop-and-go instructions. Nikoleris, Gupta, and Kistler calculate that stops and corresponding accelerations at Dallas/Fort Worth International Airport (DFW) amount for 18 % of the fuel spent on ground [NGK11, p. 304]. These technical constraints together with the operational challenge of increased traffic demand presented in Section 1.3 lead to the investigation and development of alternative taxi procedures and technologies. While single-engine taxiing describes an alternative taxi procedure with conventional technologies, on- and off-board electric propulsion systems for taxiing rely on the integration of innovative technologies.

1.3.5.1 Single-Engine Taxi Out

As running all engines on idle during taxiing generally produces more thrust than required, benefits in fuel burn can be reached by implementing single-engine taxi out (SETO) for twin-engine aircraft and twin-engine taxi out for four-engine aircraft (in the following the acronym SETO is used for both aircraft types) [Air04]. Besides the positive effect of reducing fuel consumption, a case study of Kumar, Sherry, and Thompson reveals that SETO has the potential to reduce emissions significantly [KST08].[4] Airbus estimates general fuel reductions of one third when implementing SETO for the A320 family [Air04]. The procedural steps for SETO are described in the Airbus Flight Crew Operating Manuals [Air04]. Previously having spoken out against SETO, Boeing meanwhile states that taxiing with a reduced number of engines running can be implemented if “airline policy, procedures and training are appropriately applied” [The08, p. 0.4.4]. EUROCONTROL advises

[4] The study showed a potential for reducing CO, NOx, SOx, and HC emissions by 27 % at Orlando Airport (MCO) and 45 % at New York La Guardia Airport (LGA).

to apply SETO only if specific requirements are met [Hoy16]. These requirements consider minimum taxi times as well as airport and weather conditions [Hoy16].

Although fuel consumption can be reduced, several airlines do not incorporate SETO into the operator's standard operating procedures.[5] A likely reason for this decision is the higher degree of uncertainty. As one ore more engines are started beyond the apron, engine failures are more complicated to be dealt with. Additionally, on the maneuvering area, no ground personal can monitor the engine start from outside the aircraft. Airbus further emphasizes concerns such as an increased risk of losing the braking or steering system due to less redundancy, the worse maneuverability caused by asymmetric thrust and the increased risk of foreign object damage due to the higher thrust of the remaining engine(s) [Air04].

1.3.5.2 On-Board Electric Propulsion System for Taxiing

Current concepts of on-board electric propulsion systems propose an installation of motors onto the wheels of the aircraft. In comparison to SETO, the concept allows to keep off all main engines during taxiing, increasing fuel and emission savings on ground. Furthermore, self-sufficient push-back procedures can be realized without the support of external towing vehicles. The required power can be provided by either an additional power source or the auxiliary power unit (APU).

With regard to medium-haul aircraft, Krämer calculates that applying electric taxiing powered by the APU can reduce fuel burn and emission by two third of the amount for conventional taxiing. The remaining third is caused by the APU and the running engines for warm-up at the end of the taxi phase [Krä15]. To capture the total fuel and emission savings, the whole flight cycle needs to be considered. While additional electric motors facilitate environmental-friendly ground operations, the extra weight requires a higher amount of fuel burn between take-off and landing. Re analyzes different exemplary flight missions and detects an energetic break-even at around 600 M [Re17, p. 151]. If maximum payload does not need to be reduced, the economic break-even is significantly above the energetic break even [Re17, p. 151].[6] On the contrary, the economic advantages of on-board propulsion systems are nearly non-existent if its integration involves a reduction of the payload of the aircraft [Re17].

[5] During the interviews and trials, several participating pilots reported that their airline does not allow the implementation of SETO.

[6] The non-existence of a towing tractor as well as lower airport charges and fewer engine maintenance costs lead to lower operating costs. As a consequence, deploying the on-board propulsion system on longer distances can be ecologically beneficial even if fuel burn increases [Re17].

There are two consortia developing on-board electric propulsion systems for taxiing. WheelTug aims at the integration of an electric motor onto the nose wheel [Pan+17]. The company has already announced several international airlines as launching partners and plans its entry-into-service in 2019 [Whe18; Ste18]. As the nose wheel load is about 10 % of the total aircraft weight, the friction between driven wheel and ground is noteworthy lower than on the main gear [SRH11, p. 303]. This is considered to reduce the performance in weather situations where skid is an issue [Hos14]. A joint prototype development of Honeywell and Safran is named Electric Green Taxi System (EGTS) [Joh14]. The concept of EGTS foresees the installation of motors onto the main gear. According to Hospodka, this concept enables better friction. The disadvantage, however, is that the motors are located near to the main gear brakes, which might lead to overheating [Hos14]. In 2016, Honeywell and Safran announced to halt the joint project, while Safran also claimed to continue developments regarding electric taxi systems [Gub16].

1.3.5.3 Off-Board Electric Propulsion System for Taxiing

A consequential approach to deal with the limited power and the additional weight of on-board systems for taxiing is to place the propulsion unit into an external towing vehicle. The corresponding procedure is called dispatch or operational towing. Salamone advises against the use of conventional towing tractors for towing fully loaded and fueled aircraft at high speed from gate to runway. The accelerations and decelerations place heavy stress loads on the nose gear and might exceed the fatigue limit [Sal12]. In addition to this, EASA demands the pilot in command to have full control of the aircraft during taxiing [Eur12], which cannot be ensured when the tractor driver maneuvers the aircraft-tractor combination.

TaxiBot, which was developed by Israel Aerospace Industries in corporation with TLD and Siemens, addresses these issues. The system allows for external propulsion via a tractor with the pilot maintaining control and the stress on the nose gear being limited. This dispatch towing technology holds EASA and FAA certification for the Airbus A320 and the Boeing 737 families [IT16]. After coupling, the nose wheel is placed on a movable platform which detects any forces and moments resulting from pilot's braking and steering input. After push-back, the driver switches into a pilot control mode allowing the pilot to apply brakes and tiller in the usual manner. TaxiBot steers according to the nose wheel deflection and brakes when it detects a deceleration applied via the main gear brakes of the aircraft. When no braking input is given, the tractor accelerates to a maximum speed of 22 kn

(11.3 $\frac{m}{s}$). Pilots are able to command longer phases with limited speed by realizing repeating short brake input. Automatic deceleration in terms of coast down without active braking occurs in the proximity of turns.[7]

In order to ensure the electricity and the hydraulic pressure of the aircraft during taxibotting, the APU remains switched on. Further fuel consumption is caused by the towing tractor itself, which is currently powered by diesel [SK12]. Nonetheless, simulations, calculations, and analyses revealed fuel savings between 40 % and 75 % for medium-haul aircraft towed by TaxiBot [Krä15, pp. 59-63; DB10, p. 11].[8] In line with this, exhaust gas emissions can be reduced significantly by the use of TaxiBot [Pan+17; KMR17]. Based on extensive noise measurements of different tractor- and TaxiBot-aircraft combinations at Frankfurt Airport, Hein and Baumann determine a positive effect regarding noise pollution. Consequently, ground noise at airports can be significantly reduced by the implementation of TaxiBot [HB16]. A positive side effect observed during wet weather operations is the increased maneuverability on slippery ground, caused by the increased contact face between wheels and surface.

1.3.6 Human-Machine Interfaces Supporting the Cockpit Crew During Taxiing

Regarding the maneuver of aircraft on ground, both the conventional taxi procedures as well as the mentioned alternative taxi technologies envisage a manual process. The pilot taxiing is in charge to monitor the traffic situation on the surface and to apply brakes, throttle, and tiller accordingly. The apron or ground controllers' taxi instructions need to be memorized or noted manually.[9] Although taxi speeds are comparably low and emergency stops are feasible at any location, accidents during parking and taxiing amount for 5.5 % of all fatal accidents and hull losses between 1997 and 2016 [Air17, p. 22].

To achieve a higher degree of safety during taxiing especially when visibility is low, newer aircraft offer additional HMIs supporting the pilots by presenting information on built-in displays. Optional EFB applications can provide additional

7 The operational description is based on personal observation by the author and a discussion with involved project engineers.

8 The lower value of 40 % has been communicated in an internal presentation of TaxiBot stakeholders which is not included in the references. The high variations in fuel savings between the different sources are caused by different route and speed profiles as well as by different engine start positions.

9 The description of the general taxi procedures is based on the author's observation during cockpit companionships on two medium-haul flights of a German airline and on discussion with pilots.

support to different extents. Regardless of the hardware type, the interfaces commonly present an airport moving map (AMM) with spatial and operational information provided by an aerodrome mapping database (AMDB) [Psc+11].

1.3.6.1 Built-In Taxi Interfaces

Modern Airbus aircraft like the Airbus A380, A350 and current versions of A330 and A320 are equipped with an On-Board Airport Navigation System (OANS). As shown in Figure 1.6, the OANS visualizes the airport layout including runways and taxiways as well as the current aircraft position [Cha13]. The visualization is presented on built-in displays placed in front of the pilots [Tha10].

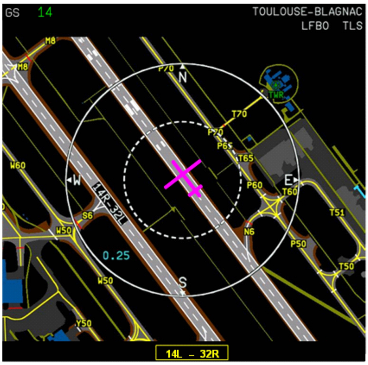


Figure 1.6.: OANS developed by Airbus running on the ND of modern Airbus aircraft (depiction with permission of Airbus Operations GmbH [Air14])

Boeing provides a similar AMM system integrated into the cockpits of Boeing 787 and 747-8 and plans to expand it to all upcoming aircraft models [CT11].

Cockpit system manufacturers like Honeywell or Rockwell Collins also offer integrated solutions displaying airport moving maps on primary displays. In addition to two-dimensional moving charts, the approaches include exo- and egocentric three-dimensional augmented visualizations of the surrounding on ground [Hon15; Hon18; Avi13].

While the extent of information presented on the AMM varies, the industry standard described in RTCA DO-272D/EUROCAE ED-99D [Eur15] provides an overview of current and future functions. These include among others taxi routing, navigation cues and traffic display [Psc+11].

1.3.6.2 Taxi Interfaces on Electronic Flight Bags

Besides the visualization on built-in devices like the ND, the referenced industry standard also considers the implementation on an EFB [Psc+11]. Definitions and regulations regarding EFBs are set by the ICAO Doc 10020 [Int15], the EASA Acceptable Means of Compliance 20-25 [Eur14a], and the FAA Advisory Circular 120-76D [Fed17]. The FAA defines EFBs as follows:

> "*An EFB hosts applications, which are generally replacing conventional paper products and tools, traditionally carried in the pilot's flight bag. EFB applications include natural extensions of traditional flight bag contents, such as replacing paper copies of weather with access to near-real-time weather information.*" [Fed17, p. 2]

An essential requirement for EFB applications is that failures of the application must not result in major hazards or have major safety effects [Fed17]. Having previously defined three EFB classes, the FAA eliminated its class definitions from the regulatory in the most recent Advisory Circular and took over the distinction carried out by EASA and ICAO. Consequently, all three regulations divide EFBs into portable and installed devices [Eur14a; Fed17; Int15]:

Portable EFBs are not part of the certified aircraft configuration and thus can be operated inside and outside the aircraft. It can be mounted to the aircraft if no additional tools for mounting or removing are needed. Installed components like the mounting unit, an optional aircraft power source, and data ports need to be part of the certified aircraft configuration. If properly secured, the portable EFB can be used during all phases of flight. [Eur14a; Fed17]

Installed EFBs are non-removable devices which are considered to be an aircraft part. Consequently, it is part of the certified aircraft configuration and is covered by the aircraft airworthiness approval. With regard to the software, it is also allowed to run non-EFB software[10] when running on a separate boot partition. [Eur14a; Fed17]

Generally, both EFB classes are allowed to run Type A and Type B software [Eur14a; Fed17]. The characteristics of the two software types are defined as follows:

[10] Non-EFB software was formerly named type C software by the FAA. As this software is no EFB software, FAA eliminated it from the current version of its Advisory Circular. [Fed17]

Type A software has no safety effect if a malfunction occurs [Eur14a; Fed17]. It must “not substitute for or replace any paper, system, or equipment required by airworthiness or operational regulations” [Fed17, p. 3].

Type B software exhibit only minor safety effects if a malfunction occurs [Eur14a; Fed17]. On the contrary to type A software, it may substitute paper products but still must not substitute or replace installed components and systems [Fed17]. In the USA, it requires “specific [FAA] authorization for operational authorization for use” [Fed17, p. 3] while in Europe an operational assessment carried out by the operator is needed [Eur14a].

Concerning airport navigation, the FAA and EASA classify AMMs as type B applications and thus allow them to run on both EFB classes. While installed EFBs running an AMM can be permanently integrated into Aircraft (if not displayed on the primary cockpit screens, see subsubsection 1.3.6.1), several airlines also allow their pilots to carry personal EFBs or provide company EFB devices with pre-installed software [Hil+15]. Common AMM modules for portable devices are included in Flight Deck Pro of Jeppesen [Jep18] or Lido/eRouteManual of Lufthansa Systems [Luf17]. In addition to the depiction of static airport elements like taxiways, runways, and stopbars, the current ownship position as well as desired taxi routes or targets can be visualized on the AMM [Jep18; Luf17].

1.4 Demand for Surface Trajectory-Based Operations

While new technologies enabling fuel-efficient propulsion during taxiing and supporting cockpit HMIs on the built-in displays or EFB are introduced into operations, the taxi procedure stays manual and route-based. The term *route-based* is used, as the apron, ground, and tower controllers provide routes and holding points without information about desired speed profiles. With regard to the previously mentioned shift of flight operations to trajectory-based operations proposed by SESAR and NextGen, route-based taxi operations imply a high degree of uncertainty. As the taxi phase marks the beginning and end of every flight and therefore builds the connecting element between two consecutive flights, unpredictable taxi times and taxi delays counteract the accuracy of the corresponding flight plan. Airport procedures and systems like A-CDM and A-SMGCS address this issue but still rely on roughly estimated taxi times (see Section 1.3.3). An increased predictability of taxi procedures leads to a more accurate estimation which could rather enhance the capabilities of A-CDM and A-SMGCS. Furthermore, taxi operations offer a high potential to reduce fuel consumptions as well as exhaust gas and noise emissions (see

Section 1.3.5). Figure 1.7 summarizes the operational, environmental, and system demands for future taxi operations and defines three optimization goals: *safety*, *ecological efficiency*, and *time efficiency*.

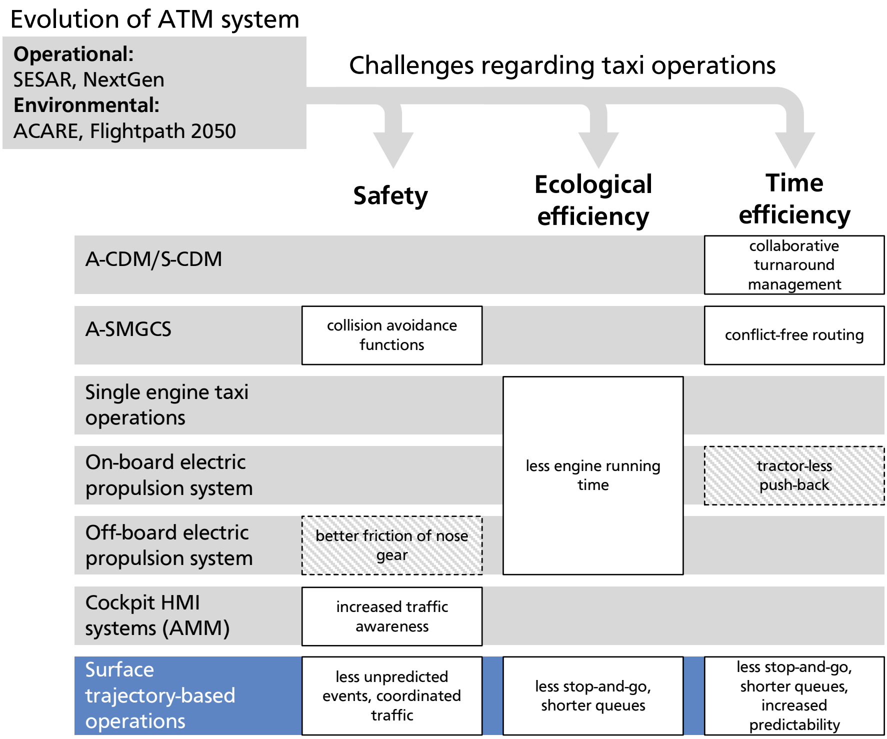


Figure 1.7.: Technologies and procedures mentioned in Chapter 1 and demand for surface trajectory-based operations

These goals are already addressed by alternative propulsion technologies and procedures (see Section 1.3.5) mainly focusing on the reduction of fuel consumption. In addition to that, AMM applications (see Section 1.3.6) help to improve the pilot's mental model of the airport and traffic situation while concurrently reducing the amount of paper in the cockpit, which might lead to a higher degree of safety.

As Figure 1.7 suggests, STBO have the potential to further enhance safety and efficiency. Equivalent to trajectory-based flight operations, STBO introduce a temporal dimension into the planning and execution of the taxi phase. While different levels of time constraints, which will be explained in the following chapter, are conceivable, all types of taxi trajectories have the common objective of enabling a coordinated conflict-free surface traffic with less unexpected events, an optimized traffic flow, and a high degree of predictability [Oku+16]. Systems like A-CDM and A-SMGCS can benefit from STBO while concurrently leveraging its implementation [OS17]. In its Aviation System Block Upgrade definition, ICAO supports this expectation by predicting efficiency, flexibility, and safety enhancements with STBO (see module B2-SURF in [Int16d, pp. 95-104]). In summary, STBO support the developments shown in Figure 1.7 by offering a new operational concept based on surface trajectories.

2 Surface Trajectory-Based Operations and Automation Considerations

Following the introduction of current taxi procedures and technologies, this chapter focuses on the surface trajectory-based operations (STBO) concept by presenting latest research activities and providing an overview of general design considerations for automated systems. The research gap leading to the innovation of this thesis will conclude this chapter.

2.1 State of Research in Surface Trajectory-Based Operations

The general concept of STBO (also known as trajectory-based taxi operations (TBTO)) is in focus of several research activities. Compared to present-day route-based taxi operations (RBTO), STBO add time-constraints to a given taxi route and thus extend the trajectory-based operations (TBO) concepts of Single European Sky ATM Research (SESAR) and Next Generation Air Transportation System (NextGen) to the ground. The amount of constraints during taxiing varies between different studies and ranges from specific required times of arrival (RTAs) to full 4D STBO in which a continuous speed profile is provided [HCF14]. Research activities deal with the trajectory generation as well as with concepts for guidance by air traffic controlers (ATCOs) and with concepts for trajectory execution by the pilot or automated aircraft. In a first step, general concepts of operations (ConOpss) for STBO are presented, followed by research regarding automated and manual execution of STBO.

In 2014, a research group of the National Aeronautics and Space Administration (NASA) Ames Research Center published a ConOps for far-term STBO [HCF14]. It defines two main phases: the first introduces STBO with the implementation of RTAs at the end of each taxiway segment, whereas in the second phase the target location is determined for every time step [HCF14]. The phase definition is motivated by a presumed traffic mix. While the first phase can be realized by means of minor adaptations of the cockpit (e.g. via an electronic flight bag (EFB)), the second phase requires further developed avionic systems [HCF14]. Therefore, the

ConOps describes a gradual shift from current operations via first phase STBO to second phase full 4D STBO. These two phases summarize specific steps in a more detailed description carried out by Foyle et al. [Foy+11]. Figure 2.1 illustrates the shift from current day operations to full 4D STBO characterized by an increasing number of constraint points (Figure 2.1).[1]

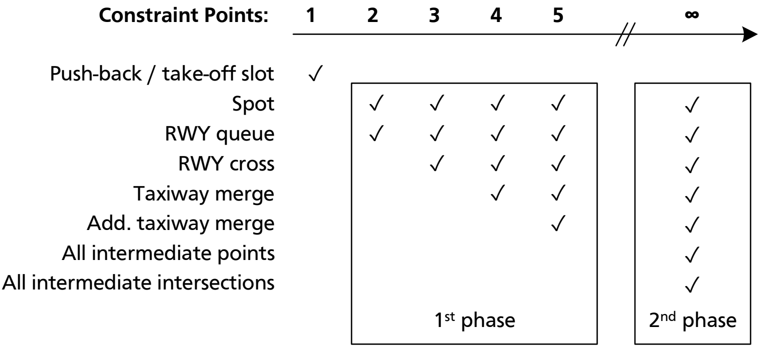


Figure 2.1.: Different amount of constraints showing the shift from current day operations to future full 4D STBO (illustrated by author on the basis of [Foy+11] including phase definition of [HCF14])

The NASA ConOps determines requirements for first and second phase STBO. Concerning the flight deck, especially the need for on-board avionics supporting RTA and 4D trajectory compliance as well as graphical pilot interfaces and advanced data communications are demanded [HCF14]. The ConOps includes detailed descriptions of nominal departure and arrival scenarios, but does not specify the amount of flight deck automation. Following an on-board optimization of the cleared taxi trajectory, the speed shall be set by throttles, either controlled manually by the pilot or automated by an auto-throttle system [HCF14].

Ensuring intensified and coordinated European and US-American approaches, the German Aerospace Center (DLR) and the NASA Ames Research Center published a joint ConOps for STBO in 2016 [Oku+16]. The purpose of the concept is to identify and describe functions and their relationship based on previous research of both facilities. The joint ConOps proposes a system consisting of the following four functions:

[1] As the concepts were developed for the US-American air traffic management (ATM) system, the RTA at the spot is the first additional time constraint. As the European system does not define spots, the taxiway and the corresponding RTAs will start immediately after push-back.

Runway scheduling schedules all runway operations including departures, arrivals, and taxi crossings while the calculated take-off times (CTOTs) from Airport Collaborative Decision Making (A-CDM) are hard constraints. [Oku+16]

Time-based taxi trajectories are conflict-free trajectories for every aircraft movement on ground, defined by a specific location at all times. Moreover, the tool calculates push-back times and recalculates several trajectories if one trajectory was violated by an aircraft and the conflict detection and resolution function decided for a replanning. [Oku+16]

Conflict detection and resolution conducts a continuous conformance monitoring and assesses the impact if a trajectory violation occurs. Depending on the determined impact, the adaption of a single trajectory or a complete replanning will be triggered. [Oku+16]

Taxi trajectory execution can be enabled by on-board modifications of the aircraft systems (e.g. STBO flight deck displays or automatic speed control) as well as ground adaptations (e.g. follow-the-greens or dispatch towing). [Oku+16]

The relationship between these functions is visualized in Figure 2.2.

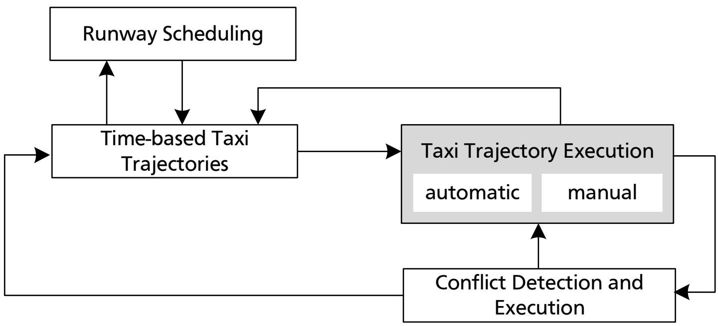


Figure 2.2.: Relationship between proposed functions of the NASA and DLR joint ConOps for STBO (illustrated by author on the basis of [Oku+16])

The ConOps highlights the challenge of the trajectory execution, as precise planning only leads to efficiency enhancements if pilots are able to follow the trajectories within small tolerances [Oku+16]. In line with the research focus in this thesis, the trajectory execution is highlighted in Figure 2.2. Investigated STBO execution concepts differ in their required amount of cockpit automation. The subdivision into automatic and manual execution is explained in the following sections.

2.1.1 Automatic Execution of Taxi Trajectories and On-Board Optimization

A study focusing on runway crossings, which are considered time and safety critical, is presented by Cheng, Sharma, and Foyle. The aim is to execute both precisely planned and fast runway crossings. The control loop consists of a linear controller calculating the required acceleration as a function of the actual and target position and a feedback-linearization controller converting the acceleration into control input (aileron, elevator, rudder, tiller, throttle, and left and right brakes) [CSF01]. Simulations showed the general applicability of the controller to enable high precision taxiing [CSF01]. The study further suggests that manual pilot input based on presented input signals does not result in higher runway crossing times than automated taxiing realized by automated control input of modified present-day aircraft [CSF01].

Sweriduk et al. describe a similar approach that investigates the execution of STBO by automating the conventional flight controls. In a first step, a list of trajectory segments is digitally transmitted from air traffic control (ATC) to the aircraft. The system is called Flightdeck Automation for Reliable Ground Operation (FARGO). It ensures the aircraft to follow the speed profile in terms of an automated control loop on-board the aircraft calculating the control input for throttle, brakes, and tiller [Swe+07]. A numerical nonlinear controller attempts to minimize the error vector between nose wheel position and the target position at the actual time [Swe+07]. A simulation including the model of a Boeing 737 shows longitudinal deviations of less than 2.5 feet (0.76 m) [Swe+07, p. 1-6]. Further research on the on-board optimization of FARGO is carried out by Cheng and Sweriduk. The evaluation results show correspondence between on-board adjusted speed profile and fuel burn, NO_X, CO_2, UHC and CO [CS09].

The automation of the control input implies the most direct conversion from trajectory generation to its execution. A presumable disadvantage resides in the fact that the pilots are completely out of the loop and may not intervene properly in case of unexpected occurrences. Apart from that, automating the control input requires aircraft modifications which need to be developed, tested, and certified.

2.1.2 Manual Execution of Taxi Trajectories Supported by Guidance Systems

Instead of investigating a direct modification of the aircraft controls, several studies deal with manual solutions with pilots being responsible to meet the required taxi speeds. Compared to automatic trajectory execution, manual solutions are better eligible for retrofit applications since the flight controls require no modifications. The necessary information about the trajectory is provided to the pilots by means of on- and off-board visualization concepts.

A research team of NASA Ames conducts extensive evaluations of on-board trajectory guidance on the basis of modified primary flight displays (PFDs) and taxi navigation displays (TNDs). Foyle et al. as well as Bakowski et al. present experiments with an advanced PFD which is modified by means of an expanded speed scale from 0 kn to 60 kn (30.9 $\frac{\mathrm{m}}{\mathrm{s}}$) [Foy+11; Bak+11]. Further iterations add a dynamic target speed bug [Foy+11], an adjusted turn speed bug, the next RTA, and the remaining time [Bak+13]. In the initial version, the TND visualizes the cleared route and surface traffic [Foy+11; Bak+11]. In consecutive designs, Bakowski et al. add an indication of the target trajectory in terms of a visualization of the allowable position deviation, the taxi start time, the advised straightway speed, and a queue-entry time [Bak+15]. Additional trials investigate different tolerance band sizes visualizing the allowable deviation [BHF17]. A generic overview summarizing the mentioned functions of the research group is depicted in Figure 2.3.

Recapitulating the simulator evaluations of the different display iterations, the following major findings concerning the support of STBO with modified primary cockpit instruments can be retained.

- The RTA conformance can be enhanced if a feedback mechanism exists [Bak+11; Foy+11].

- An increased number of constraints leads to better RTA conformance [Foy+11].

- Best trajectory conformance (supported by visual guidance) can be observed when implementing a dynamic speed bug on the PFD (RTA error of less than 10 sec in 100 % of the measured time [Foy+11, p. 8]) or the TND with all functions integrated (RTA error of less than 15 sec in 96 % of the measured time [Bak+15, p. 2462]).

- All iterations cause long dwell times on the supporting displays. The presentation of more constraint points and information on the displays limits the time frame for pilots to look out of the window [Foy+11; Bak+11; Bak+13; Bak+15].

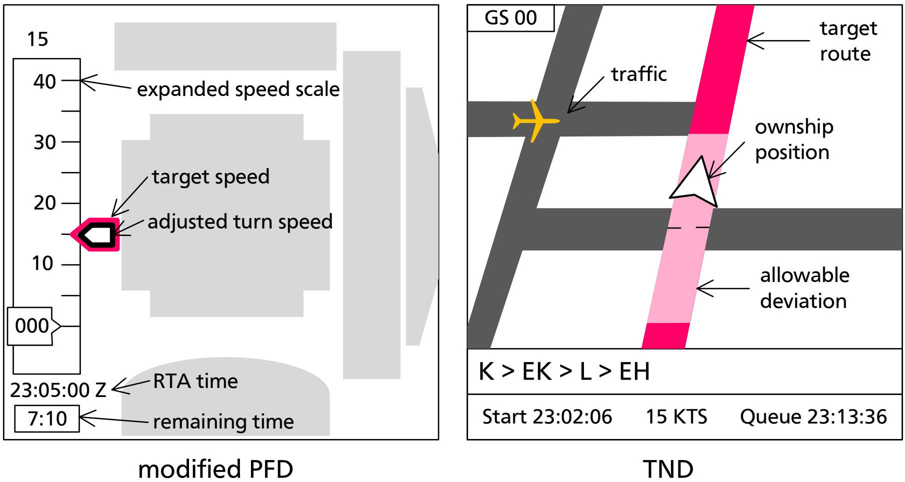


Figure 2.3.: Schematic summary of the functions integrated into the PFD and TND in [Foy+11; Bak+11; Bak+13; Bak+15] (illustrated by author)

- Larger tolerances lead to longer eyes-out-the-window times, increase the time the aircraft stays inside the allowable position deviation, but also increase the error between expected and actual position [BHF17].

In contrast to these concepts, further studies deal with different visualization devices like a head-up display (HUD). Cheng, Andre, and Foyle describe simulator trials evaluating the use of a HUD. Results point out that meeting specific RTAs during taxiing requires the presentation of additional information about the relevant speeds. The qualitative feedback of evaluating pilots shows that most participants consider the indicator of the required and current speed most important to solely rely on. Accordingly, the trials demonstrate that information presented shall not be redundant and the presentation of speed information has better usability than time information (e.g. provision of RTAs) [CAF09]. These findings are strengthened by an investigation comparing the usability of time and speed information to support STBO. Therefore, a HUD shows the required speed to meet an RTA at an intersection, directly shows the RTA at an intersection, or both [Foy+11]. Results reveal that the absolute error between required and actual arrival time at the intersection is comparatively large when only showing the RTA and small when showing RTA and speed [Foy+11]. Both studies demonstrate the general applicability of HUDs and its advantage of enabling parallel monitoring of the outside traffic situation.

Complementary to head-down and head-up displays, Urvoy developed a system providing trajectory information to the pilot while enabling to focus on the taxiway. Dynamically switched taxiway centerline lights provide information of both the target route and the desired speed [Urv14]. In simulations with two different controller concepts, maximum position deviations of −200 m and 400 m and positive usability ratings were observed [Urv14, p. 90]. Moreover, Urvoy diagnoses a high intuitiveness of the dynamic follow-the-greens concept [Urv14].

2.2 Designing Automated Systems

All previously presented approaches for STBO require a cooperation between human and automation. Corresponding models and methods utilized in this thesis are presented in the following subsections. After outlining the applied user-centered design approach, the constructs *situation awareness* and *usability*, which are analyzed by the hypotheses presented in Section 3.6, will be explained. Subsequently, considerations concerning degrees of automation are reflected.

2.2.1 User-Centered Design

As many developments and innovations are driven by enhanced technology, the operator's integration is often considered by means of a technology-centered design process. After having specified the system, the human-machine interface (HMI) is developed to present all available information. Cockpit systems are mainly developed by engineers, who – due to a different professional education – face issues in a different manner than pilots do. Resulting designs can thus be very challenging for the operating pilot [Hec14]. Endsley addresses the finding that more complex systems produce more data, whilst the provision af all available data to the operator causes even less understanding [End00]. An approach to deal with this challenge is the application of a user-centered design process, placing the system user and her or his needs in the focus of development. Endsley, Bolté, and Jones state that in a user-centered design process, technology shall be organized around the users' goals, tasks, and abilities as well as around their way of processing information and making decisions. Furthermore, users must be kept in control of the systems in order to avoid being out-of-the-loop [EBJ03]. Guidelines for user-centered design were formulated by several researchers like Schlick, Bruder, and Luczak [SBL18] as well as Endsley, Bolté, and Jones [EBJ03].

The user-centered design process is also recommended by international standards. The approach of this thesis is based on the standard DIN EN ISO 9241-210

[DIN11]. An adapted visualization of the iterations proposed by the norm serves as the basis for the HMI design in this study and is shown in Figure 3.1 of Section 3.1.

Besides the standard defining the user-centered design process, general user-oriented design principles are listed in DIN EN ISO 9241-110 [DIN08]. This norm recommends the following principles for HMI design [DIN08]:

- Appropriateness regarding task
- Self-descriptiveness
- Conformance with expectations
- Learning support
- Controllability
- Fault tolerance
- Suitability for customization.

The applicability of the individual principles needs to be revised with respect to the specific context of use [DIN08].

2.2.2 Situation Awareness and Traffic Awareness

Situation awareness is a construct in focus of several human factors evaluations. A brief definition of situation awareness is provided by Endsley:

> "*Situation Awareness 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.*" [End88, p. 792]

In line with this definition, Endsley further defines three levels of situation awareness. As visualized in Figure 2.4, level 1 situation awareness defines the perception of environmental aspects and is therefore essential for the subsequent steps [End95]. Having perceived the environment, level 2 situation awareness describes the comprehension of the situation with regard to individual goals. This second step varies between operators, as it depends on personal skills and experience [End95]. Level 3 situation awareness eventually deals with the projection of the current state by estimating future states [End95].

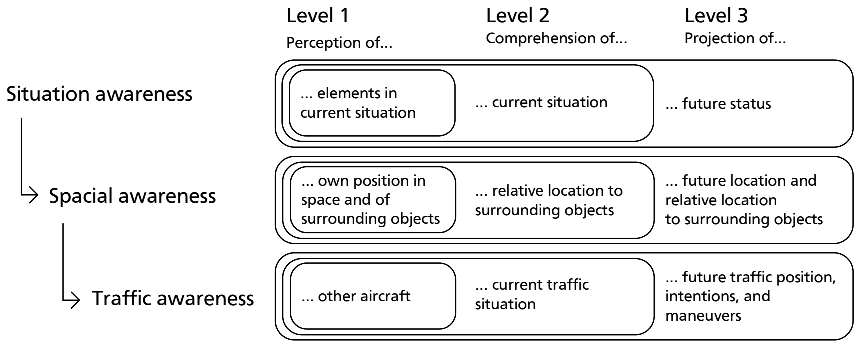


Figure 2.4.: Three levels of situation, spacial, and traffic awareness according to [End95; WH00; San16] (illustrated by author)

Wickens further distinguishes between spacial, system and task awareness as subsets of situation awareness. In the context of aircraft operations, the concept of spacial awareness deals with the perception, comprehension, and projection of the position and orientation of the own aircraft along with surrounding aircraft and other objects [Wic02]. Focusing on the relationship between ones position and surrounding traffic, Santel defines traffic awareness as a further sub-category of spacial awareness [San16]. As visualized in Figure 2.4, the subcategories of situation awareness are also subdivided into three levels.

There are different opinions about the construct of situation awareness and its application. Dekker and Hollnagel claim that the situation awareness model as described by Endsley is like a "folk model" [DH04]. They state that looking at the loss of situation awareness merely does not provide any hint about the real source of an accident. They further consider the model to be immune to falsification [DH04]. In contrast, Parasuraman, Sheridan, and Wickens counter the view of Dekker and Hollnagel by referring to the large science base of studies demonstrating the applicability of the construct and its distinctiveness to performance measurements [PSW08].

2.2.3 Usability

The term *usability* is defined by the international standard DIN EN ISO 9241-210 as:

> *"The extend to which a system, product, or service can be used by specific users in a specific usage context to achieve defined goals effectively, efficiently, and satisfactorily." (translated from German by the author)* [DIN11, p. 7]

Correspondingly, usability comprises effectivity, efficiency and user satisfaction. While effectivity measures precision and the completeness of a task, efficiency describes the ratio between effort and effectivity [DIN11]. Besides these two performance indicators, user satisfaction characterizes the subjective sensation of the user toward a system [DIN11].

Even though the evaluation of usability originates in software development, a transfer to general human-machine systems is reasonable [SBL18]. As possible applications are versatile and need to be assessed in their individual context, comparing usability ratings of different applications is not expedient. However, the evaluation technique System Usability Scale (SUS) developed by Brooke is one standardized method often applied for measuring the usability subcategory of user satisfaction [Bro14]. Besides comparing systems of the same context, a study by Bangor, Kortum, and Miller revealed that SUS scores can also be interpreted in terms of an adjective rating [BKM09].

2.2.4 Degree of Automation

Following a user-centered design approach in the development of a human-automation system has the objective to achieve high situation awareness and usability. Endsley, Bolté, and Jones indicate the following main issues of automated systems regarding situation awareness [EBJ03]:

- out-of-the-loop syndrome
  - caused by complacency and loss of vigilance
  - caused by passive processing
  - caused by poor feedback quality
- level of understanding the automation
- decision support dilemma.

The out-of-the-loop syndrome describes the phenomenon that system operators lose their ability to manually take over automated systems in case of automation failures. As shown in flight simulation trials, the presence of concurrent tasks can even strengthen that effect [PMS93]. Common causes for an operator to be out-of-the-loop are complacency and loss of vigilance. In this context, the term complacency describes the presence of a sense of security based on the existence of automation support. Moray states that complacency cannot just be described as a human error. Even if a person allocates its limited resources according to the individual probabilities of failures, not every fault can be detected [Mor00]. Vigilance is a state resulting from an increased level of arousal, allowing the operator to "react to small changes in the environment" [KSZ15]. Passive processing causes lower awareness of a situation as the operator is not actively involved in the procedures [Gal+01; MP01]. Poor quality of the system feedback which is the third factor facilitating the operator to be out-of-the-loop can be counteracted by the application of human factors design principles [EBJ03].

Even if the system functions as planned, operators need to understand the system properly in order to interpret and project a situation. A low level of understanding causes an inaccurate mental model and thus affects level 2 and level 3 situation awareness [EBJ03]. This is backed by a three-year field study with airline pilots conducted by Wiener revealing several cases in which pilots do not fully understand the automation of aircraft [Wie89].

The decision support dilemma describes the issues of serial systems in which automation provides advice while the operator conducts the action manually. As both the advice provided by the automation and the final decision of the human may be flawed, the overall reliability of such systems decrease [SM87].

According to Endsley and Kiris, a correlation between an increased level of automation and the loss of situation awareness can be observed, which leads to the often discussed question which tasks should be automated and which should be not. Following the initial approach to automate every technically possible aspect, more recent approaches take the individual strengths and weaknesses of humans and machines into account [DW02]. As a result, lists defining what men are better at and what machines are better at (men are better at / machines are better at (MABA-MABA)) were generated [DW02].

According to this approach, scientists defined possible levels of automation. Vagia, Transeth, and Fjerdingen present a summary of defined automation modes in literature, which was expanded by Mhlanga [VTF16; Mhl17]. One frequently cited categorization into ten levels was developed by Parasuraman, Sheridan, and Wickens on the basis of previous approaches [PSW00; SV78]. A similar categorization is developed by Endsley and Kaber [EK99]. The defined levels range from zero to complete automation. Each level is specified by its task allocation of monitoring, generating, selecting, and implementing [EK99]. Those and further concepts have in common to function as a guide to developers. Having defined the aim of automation, different degrees of automation are suggested. Correspondingly, the level definitions are still based on the MABA-MABA concept.

Arguing modern systems should aspire a cooperation between human and machine, Dekker and Woods advise to reject the MABA-MABA approach. They rather conclude that "the more pressing question today is how to make humans and automation get along together" [DW02, p. 243]. Weyer supports this view by demanding users' confidence in hybrid collaboration instead of trust in automation [Wey15]. Addressing the requirement for collaborative automation modes with different degrees of cooperation between human and automation, SESAR proposes a differentiated taxonomy. Analogous to the classification of Endsley and Kaber, this concept defines the four functions *information acquisition*, *information analysis*, *decision and action selection* as well as *action implementation* [ENA+13]. A system can include all or a subset of these functions and every function can be implemented in terms of several degrees ranging from zero to full automation [ENA+13].

2.3 Research Gap and Innovation of this Thesis

After having presented the need for STBO in Section 1.4, Chapter 2 consequently deals with the presentation of different research approaches investigating STBO. By means of a ConOps, the far term objective of continuous full 4D STBO (second phase in Figure 2.1) has been formulated. The referenced studies regarding STBO execution are summarized in Table 2.1 showing that three different approaches are being evaluated. Precise continuous speed profiles (full 4D STBO) can be realized by automation of the aircraft avionics. Therefore, the automation of thrust and brake controls are mandatory, while additional automated steering enables further relief of the pilots. Besides the suitability for full 4D STBO, this concept is best suited for upcoming aircraft generations, which might be equipped with electric on-board propulsion systems (e.g. [OB17]) allowing for a straightforward automated speed control. Applying the concept to current aircraft entails a high amount of modifications and certification and thus stands for a disproportionate effort. In contrast, the concepts of manual trajectory execution with pilot guidance systems can be realized by fewer (on-board support) or no aircraft modifications (off-board support). While simulations showed promising trajectory tolerances, the execution of dynamically changing continuous 4D speed profiles can only be realized by a great amount of pilot attention, corresponding to a high degree of workload. Hence, the manual taxiing concepts allow for initial implementations of STBO, whilst the suitability for full 4D STBO is assessed to be low.

Table 2.1.: Overview and categorization of research activities and concept of this thesis

Approach	**Sources**	**Trajectory execution**	**Required A/C modifications**	**Full 4D STBO precision**
Automated taxiing	[CSF01; Swe+07; CS09]	automated	avionics	+
Manual taxiing with on-board support	[Bak+15; Bak+11; Bak+13; Foy+11]	manual	primary cockpit instruments	−
Manual taxiing with off-board support	[Urv14; Hau+11]	manual	none	−
Trajectory-based dispatch towing (TBDT)	Bernatzky	cooperation	none*	+

* For the purpose of comparison, automation modes with modification of brake control will be evaluated as well.

As shifts in ATM operations are generally realized gradually, full 4D STBO may be deployed even though not all aircraft provide automated speed control. The resulting heterogeneous traffic mix leads to a high risk to negatively influence the performance of the surface operations, as conventional taxiing aircraft represent a disturbing factor in the trajectory-based system. As the presented manual approaches require on-board or off-board adaptations and only allow for a limited amount of trajectory conformance, the aim of this thesis is to present an innovative approach which meets the following key requirements:

- allowing for full 4D STBO
- suitable for present-day aircraft
- no extensive modifications and re-certification of the aircraft (easily retrofitable)
- no infrastructural adjustments of airport surface.

The subsequent approach of this thesis addressing these requirements will in the following be referred to as trajectory-based dispatch towing (TBDT). In consideration of the dispatch towing technology TaxiBot, presented in subsubsection 1.3.5.3, a further automated version of the tractor shall be responsible for accelerating and decelerating an aircraft according to a predefined full 4D trajectory. As the applicable acceleration and deceleration is limited to the fatigue limit of the nose gear, harsh brake commands need to be supported by the aircraft brakes. In order to provide the cockpit crew with the corresponding information, a portable EFB shall function as the HMI. With this approach, outlined in Figure 2.5 and determined in detail in the upcoming sections, present-day aircraft can be integrated into full 4D STBO without further modifications.

This thesis describes the first investigation of the pilot's integration into TBDT. Following the concept development, a real-time simulator study enables the application of human factor methods in order to gain insight about the general suitability of the concept as well as the evaluation of different degrees of automation. Focusing on TBDT, the evaluation shall reveal how the cooperation between humans and automation can be best achieved (in line with the claim of Dekker and Woods formulated in Section 2.2.4).

In Section 2.2.3, usability is divided into effectivity, efficiency, and user satisfaction. Among the performance measures (effectivity and efficiency), effectivity is directly linked to the quality of trajectory conformance, which is a basic goal of TBDT, and needs to be analyzed. Efficiency additionally considers the effort

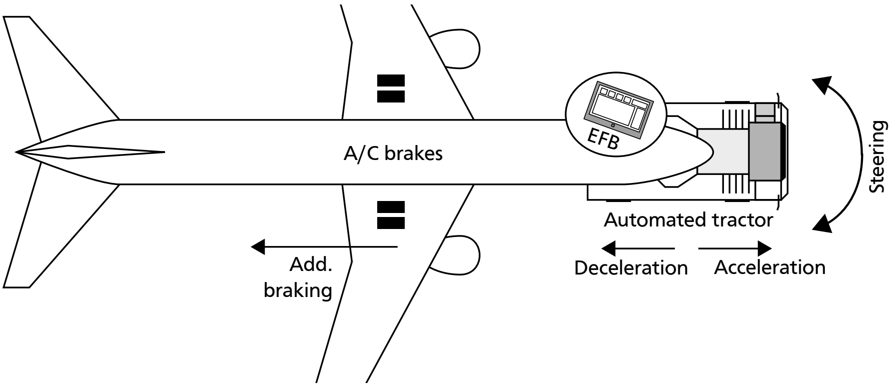


Figure 2.5.: General implementation concept of TBDT as developed and investigated in this thesis

(work load), which obviously is expected to correspond to the degree of automation and thus will not be investigated in detail.[2] Therefore, in the following, the term *performance* is limited to effectivity. The subjective component of usability (user satisfaction) is essential to be considered when introducing new systems and procedures for the cockpit crew and thus needs to be assessed in this study. One basic concern of previous research on STBO implementations is the reduced eyes-out-the-window time leading to reduced traffic awareness. Consequently, the relationship between TBDT and traffic awareness will be evaluated. The motivation for STBO is based on operational benefits and does not explicitly consider the cockpit crew. Therefore, the fourth investigated aspect is the pilot acceptance toward the novel system.

Specific hypotheses relating to the individual automation modes are developed in Chapter 3. Based on the previous illustration of different STBO approaches and the general concept drafted in Figure 2.5, this chapter concludes with the following global hypothesis:

> **Global Hypothesis:** Pilots can be integrated into TBDT in an acceptable manner with regard to performance, traffic awareness, user satisfaction, and acceptance.

[2] Not included in the investigated hypotheses, the effort has not been analyzed in detail. However, Appendix I shows descriptive results of the Raw Task Load Index (RTLX) ratings.

3 Concept Development for Trajectory-Based Dispatch Towing

This chapter starts with presenting the development approach for a prototype system. Thereafter, a macroscopic operational scenario description specifies the context of use. Considering the role of pilots, the following section presents requirements regarding their integration into trajectory-based dispatch towing (TBDT). The successive concept development comprises the trajectory control and the supporting cockpit human-machine interface (HMI). Taking into account both the global hypothesis and the developed concept, this chapter concludes with four (partially further subdivided) main hypotheses and corresponding measurements.

3.1 Approach to System Design

The development approach as presented in Figure 3.1 can be separated into two main aspects (trajectory control concept and user-centered HMI development), which are embedded in the process and scenario design and the main simulator evaluation.

Based on a literature review, on-site visits, expert interviews, and a cockpit observation of two medium-haul flights, the current procedures and future developments are summarized in Chapter 1 and Chapter 2. The corresponding process and scenario description was accompanied by a joint study of TU Braunschweig and TU Darmstadt and was discussed and adjusted in a user forum [HSF17; Ber18]. The participants of the user forum between stakeholders were composed of employees from an airline, an airport operator, an air navigation service provider (ANSP), as well as of pilots and researchers. As a result, an operational concept defining the stepwise introduction of TBDT into current and future airport procedures was generated.

In accordance with the aim of this study, the subsequent development steps focus on a single aircraft following a predefined trajectory. While the trajectory generation, modification, and optimization is being investigated in different research projects (e.g. [Re17; Swe+07; GT12; LSB10]), the trajectory control concept defines how typical speed profiles need to be designed in order to match the capabilities of the tractor-aircraft combination. In addition, the concept outlines the

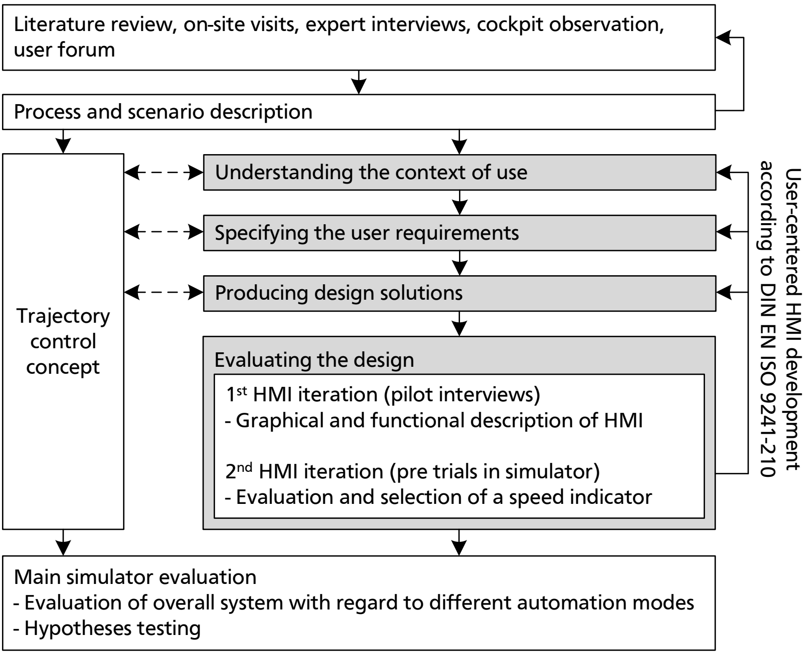


Figure 3.1.: Approach for developing a prototype system with HMI design process after DIN EN ISO 9241-210 highlighted in gray (illustrated by author incorporating components of [DIN11])

characteristics of an inner control loop, ensuring the precise execution of target trajectories with optional pilot integration.

Along with the definition of the control concept, a user-centered design approach according to DIN EN ISO 9241-210 [DIN11] was applied for the cockpit HMI design. As explained in Section 2.2.1, this process includes several iterations. With respect to this study, two major evaluations led to a prototype design.

The implementation of the control logic and the HMI enabled the main simulator evaluation. In addition to the investigation of the applicability of the HMI, the final evaluation provided insight about different automation modes.

3.2 Process and Scenario Description

The process and scenario description starts with a presentation of the roles and responsibilities of the stakeholders in the TBDT concept. On the basis of these determinations, the operational concept of the cockpit procedures will be presented in terms of a stepwise description. Having a closer look at the pilots' role, levels of automation regarding braking and steering will be defined.

3.2.1 Roles and Responsibilities

An essential outcome of the user forum, described in [Ber18] and [HSF17], is the definition of involved roles and their responsibilities. The pilots are the center of the concept and mainly interact with the controllers. In contrast to the conventional responsibility distribution discussed in Section 1.3.1, the redefined roles of apron and ground control do not differ and can thus be unified. Additionally, a tractor driver and a ramp agent (also referred to as walk-out assistant) are actively involved in the TBDT process. Table 3.1 summarizes the individual roles. If no additional note is provided, the responsibilities apply to all investigated automation modes. The distinction between pilot taxiing and pilot monitoring is carried out in Section 3.2.2. Further roles, like aircraft and tractor dispatchers or airport operators, not mentioned in Table 3.1 are slightly affected by TBDT but not actively involved in the considered taxi procedure.

In accordance with the overview of responsibilities for the general surface trajectory-based operations (STBO) process by Hooey, Cheng, and Foyle [HCF14], the role *automation* is also part of the TBDT process. Table 3.2 lists the key tasks of the automation instances *4D-SMAN* and *tractor*, with their functional realization discussed in Section 3.4.

Table 3.1.: Overview of roles and responsibilities in TBDT

Role	Responsibilities
Pilots	• revise planned and cleared taxi routes • accept or decline cleared taxi segments • monitor surrounding and traffic situation • apply brakes and/or tiller according to HMI advice (if intended by automation mode) • apply brakes and/or tiller in emergency situations • contact controllers via voice communication in emergency or unclear situations
Controllers*	• revise trajectories presented by trajectory-based surface manager (4D-SMAN) • clear trajectory segments if no safety concerns exist • trigger generation of new trajectory if safety concerns exist • advise pilots via voice communication in emergency or unclear situations
Tractor driver	• drives tractor manually to and from aircraft • initiates coupling and de-coupling process • hands over control to aircraft and trajectory automation prior to target push-back time (TPBT) • monitors traffic situation • engage emergency braking in safety critical situations • checks visually for proper engine running and provides hand signal to pilot after de-coupling
Ramp agent	• ensures that all turnaround processes are completed prior to TPBT • confirms aircraft-ready status to system prior to TPBT • supervises automated push-back process • provides hand signal for emergency braking to pilot if safety critical situation during push-back occurs

* The responsibilities of apron, ground, and tower controllers do not differ significantly in the TBDT concept and are therefore presented as one instance.

Table 3.2.: Overview of automation instances and responsibilities in TBDT

Automation instance	Responsibilities
4D-SMAN	• generates taxi trajectories for all taxiing aircraft • presents planned trajectory to controllers • sends cleared trajectories to tractor-aircraft combination • provides TPBT (in cooperation with Airport Collaborative Decision Making (A-CDM)) • monitors trajectory conformance of aircraft • recalculates trajectories if trajectory conformance of individual aircraft is too low
Tractor	• accelerates and decelerates aircraft according to trajectory • adjusts speed profile if small position deviations occur • steers according to trajectory (if intended by automation mode) • detects braking and/or steering input of pilot and acts accordingly

In order to maintain a homogeneous air traffic control (ATC) system at airports, even though not all aircraft are conducting TBDT, the defined roles and responsibilities are also applicable to further propulsion concepts. Aircraft equipped with on-board automated propulsion systems need to be included into the 4D-SMAN trajectory generation by means of adapted performance characteristics. Conventionally taxiing aircraft can be considered by the 4D-SMAN by applying significantly higher safety margins and position tolerances. Nevertheless, the amount of aircraft able to follow full 4D trajectories will highly affect the performance of the system (see [HCF14] for general STBO).

3.2.2 Operational Concept

Regardless of the automation mode, the proposed TBDT process is composed of specific operational steps. An exemplary route at Frankfurt Airport is shown in Figure 3.2. The following description of the taxi-out segments highlighted in this figure is supplemented by the swim-lane diagram in Figure 3.3.

- **Turnaround and arrival of tractor**
  In regards to communication, the proposed procedures are in line with the

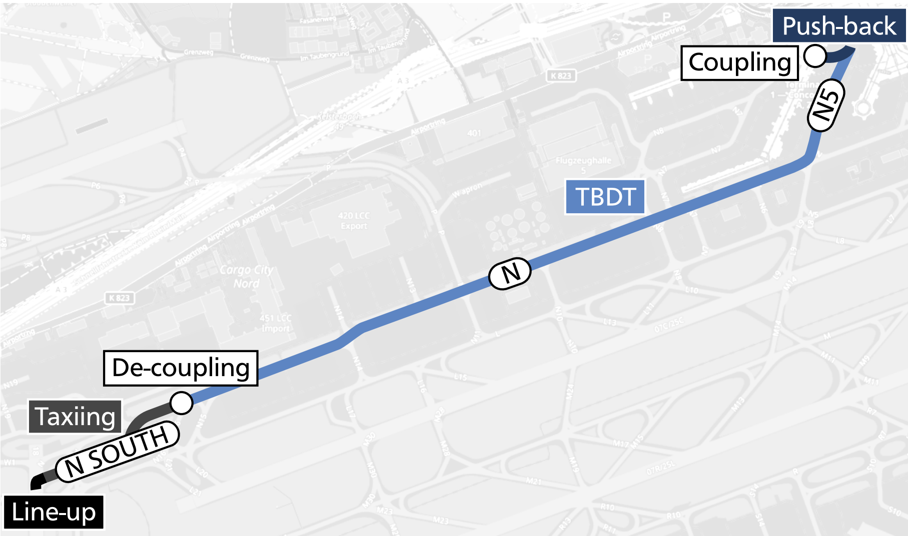


Figure 3.2.: Exemplary route and segments of a TBDT procedure (map data copyrighted by OpenStreetMap contributors available from https://www.openstreetmap.org)

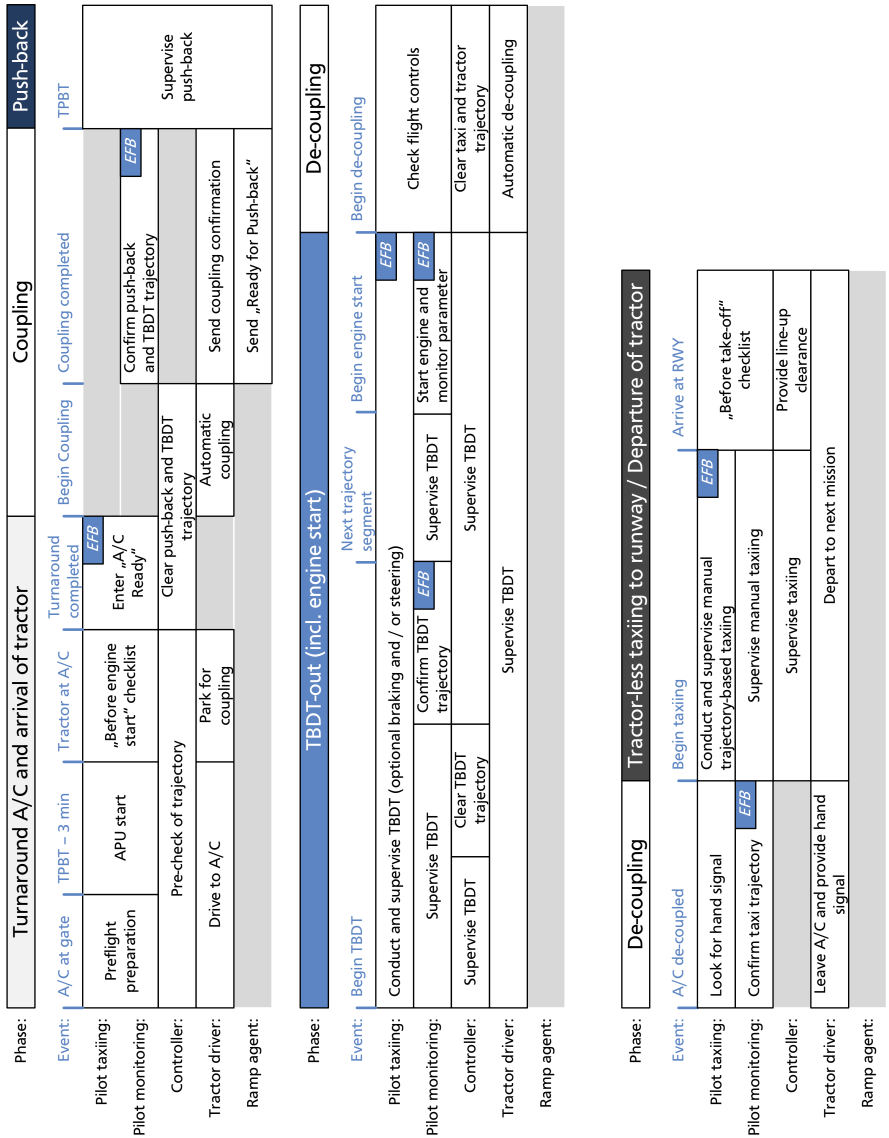


Figure 3.3.: Swim-lane diagram of TBDT-out process (TBDT-related tasks only)

Single European Sky ATM Research (SESAR) concept of operations (ConOps), which proposes voice-less communication via a pilot-controller data link [SES17]. Radio communication shall be reduced to unplanned situations only, enabled by a new control philosophy. Instead of pilots actively requesting clearances, all instances shall follow predefined target times provided by the central 4D-SMAN. This effects the predictability requirements toward the turnaround activities, as delays will cause a recalculation of all affected trajectories. A smooth process requires the tractor to arrive at the aircraft as well as one pilot confirming the aircraft being ready via the electronic flight bag (EFB) HMI prior to the TPBT. Furthermore, the responsible controller needs to revise and clear the first trajectory segment as defined by the 4D-SMAN in time.

- **Coupling**
  Coupling can start when the turnaround is completed and has to finish prior to the TPBT. For safety reasons, one pilot as well as the walk-out assistant shall confirm the coupled state.

- **Push-back**
  The push-back path marks the first trajectory segment and can be conducted both manually by the tractor driver or automatically. In both cases, the walk-out assistant, the pilot, and the tractor driver need to oversee the process and intervene in emergency situations.

- **TBDT-out**
  During TBDT, the 4D-SMAN defines the trajectory and presents it to the controller who needs to clear it segment-wise if no safety concerns arise. According to the International Civil Aviation Organization (ICAO) specifications in its Aviation System Block Upgrade definition [Int16d], the target route is sent digitally to the aircraft allowing for visualization on the EFB. The pilots can revise the planned and the cleared segments on their EFB and need to confirm cleared segments in order to allow for automatic execution by the tractor. Depending on the automation mode as defined in Section 3.2.3, the pilots may need to support the tractor by means of braking or steering. Regardless of the chosen automation mode, the cockpit crew stays responsible for a safe taxi process and has to intervene by means of manual braking or steering input in safety-critical situations. Communication via radio shall be limited to these extraordinary situations.

- **Engine start**
  The engines need to be started manually during taxiing by the pilot monitoring. The exact time step for engine start will be calculated by the 4D-SMAN.

As shown in Figure 3.4, the target time for engine start ensures the engines being warmed-up when entering the runway.

- **De-coupling**
  The time and location for de-coupling is calculated by the 4D-SMAN as well. Figure 3.4 explains the flexible time-window for the decoupling process allowing to adapt to the airport infrastructure and surrounding traffic. The successful de-coupling and proper engine running shall be confirmed by a hand signal of the tractor driver.

- **Departure of tractor**
  After de-coupling, the tractor driver needs to leave the maneuvering area via the shortest route. Yet, the tractor has to drive in the controlled area for a given distance. As a consequence, the tractor has to be equipped with a transponder and the driver shall be on standby for radio communication (see [Fra18]).

- **Tractor-less taxiing to runway**
  In order to allow for the engines to warm up and to avoid tractors driving on the runways, within the last taxi segment, pilots shall taxi their aircraft conventionally propelled by the engines. As target speeds are set manually via thrust and brakes only, the trajectory tolerances need to be extended (no full 4D STBO).

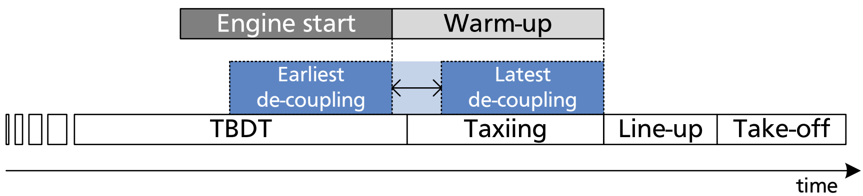


Figure 3.4.: Time line for final TBDT steps

For TBDT-in, the operational steps are similar to the departure process. The corresponding swim-lane diagram is shown in Appendix C. The flexible coupling position of tractor and aircraft next to the runway is the major difference to TBDT-out. As the actual runway exit is a matter of individual safety decisions by the pilot, the planned coupling position needs to be located at an adequate distance. Due to cool-down issues, the engines cannot be shut-down immediately after landing. Accordingly, conventional taxiing needs to be considered as an alternative when taxi-in routes are short and the traffic density is low.

3.2.3 Defining Levels of Automation

Besides evaluating the general applicability of the TBDT concept (see global hypothesis in Section 2.3), this study shall define which automation mode is most suitable concerning the integration of the pilot. In order to understand the relationship between cause and effect, the number of variables needs to be limited to a reasonable amount. Thus, the following distinction is carried out by a focus on the task of maneuvering the aircraft. This thesis further concentrates on the TBDT phase beginning after push-back and ending before engine start. Parallel tasks such as working through checklists or conducting pre-departure briefings can be automated as well, but are not directly related to TBDT.

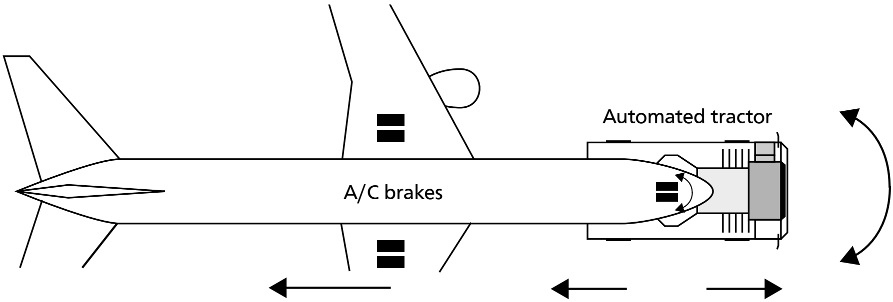
With respect to maneuvering the tractor-aircraft combination, four main tasks exist:

- Accelerating via tractor
- Decelerating via tractor
- Braking via aircraft
- Steering via tractor (optionally triggered by aircraft nose wheel)

Referring to the concept derivation in Section 2.3, a major motivation of TBDT is the expected high degree of trajectory conformance an automated tractor allows for. Hence, implementing a concept to manually accelerate and decelerate the tractor would counteract this benefit. Consequently, as depicted in Figure 3.5, the functions *deceleration* and *acceleration* of the automated tractor need to be automated in order to enable precise 4D trajectory execution. Having determined the automatic acceleration and deceleration, the functions *braking* and *steering* remain optional for manual control.

Trajectory conformance is expected to be best when the aircraft brakes are automated as well, enabling the precise execution of harsh decelerations. However, automating the brakes requires an essential modification of the avionics which results in high certification efforts. This does not match with the previously mentioned requirement of no or minor modifications of the aircraft. Furthermore, phases of manual brake input can be minimized in advance by the trajectory generation tool. Yet, applying the aircraft brakes will still be necessary in given situations and the possible automation of the aircraft brakes shall be investigated in detail.

Concerning the steering mechanism, both the manual and the automatic steering can be realized without further modifications. If steering is automated, the tractor directly deflects its wheels according to the predefined trajectory. As an alternative,



	Braking	Deceleration	Acceleration	Steering
Mandatory automation for TBDT (full 4D STBO)	no	yes	yes	no
Input device for manual execution	pedals	pedals	- no device - (engines off)	tiller

Figure 3.5.: Automation concept for TBDT

the pilot may apply the tiller, causing the nose gear to steer. In the latter case, the tractor operates like the conventional TaxiBot, detecting the nose wheel deflection and steering accordingly. The impact of the steering mechanism on the trajectory conformance is expected to be low. Thus, manual or automated steering is conceivable. The investigation of both manual and automated steering shall provide insight into the relationship of the pilot being in-the-loop and the amount of mental capacity for TBDT-related tasks.

Summarizing these considerations, the two independent variables *braking* and *steering*, which have the states *automated* or *manual*, can be identified. The combination of the independent variables result in four different modes of TBDT, summarized and numerated in Figure 3.6. Completed by the conventional tractor-less taxi process of route-based taxi operations (RBTO), five different automation modes provide the basis for further concept development as well as for the concluding evaluation.

With regard to the automation taxonomy suggested by SESAR (see Section 2.2.4), the functions *information acquisition* and *information analysis* do not vary within this automation concept. The functions *decision and action selection* as well as *action implementation* range between manual, mixed automation and full automation – depending on the TBDT mode.

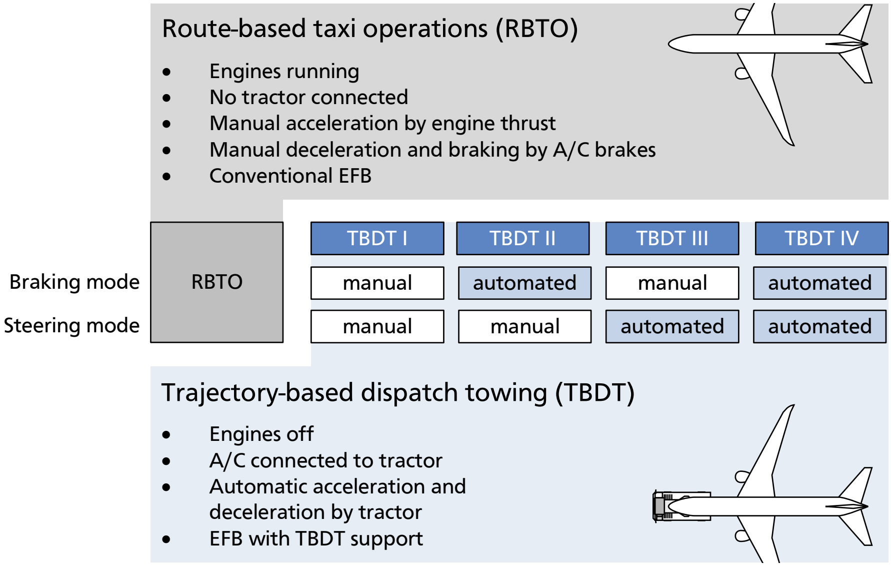


Figure 3.6.: Overview of five automation modes TBDT I to IV and RBTO

3.3 Requirements for Pilot Integration

Although the TBDT modes differ in their automation, all modes need to meet several compulsory requirements regarding pilot integration. In accordance with the global hypothesis (see Section 2.3), the following sections compile essential requirements with respect to performance, situation awareness, traffic awareness, subjective usability, and acceptance. Taking into account the procedural TBDT steps of Section 3.2.2, the human factors considerations are supplemented by functional HMI requirements.

3.3.1 Performance Requirements

The main objective of TBDT is to enable aircraft to follow an optimized trajectory as accurately as possible (full 4D trajectory). A higher expected trajectory conformance enables the trajectory generation to consider lower uncertainties, which increases its flexibility. Furthermore, high deviations between actual and planned position may result in safety critical situations when other aircraft, vehicles, persons, or objects are involved.

While target accuracies depend on the individual generation algorithms, the airport layout, and the traffic density – which are not evaluated in this study –, maximum position errors are defined with regard to safety considerations. In Doc 9830, ICAO specifies requirements for the Advanced Surface Movement Guidance and Control System (A-SMGCS) and defines parameters and margins for longitudinal spacing of aircraft [Int04, pp. 3-10,3-11,4-2,4-3]. Applying this approach to the use case of a towed aircraft taxiing behind another aircraft, as shown in Figure 3.7, reveals a maximum allowable longitudinal position error of $(\Delta s)_{crit} = 22\,\text{m}$. This value results from the worst case scenario with the preceding aircraft braking unexpectedly. The imminent conflict is detected by the monitoring system, providing brake advice to the following pilot, who then engages the brakes accordingly.

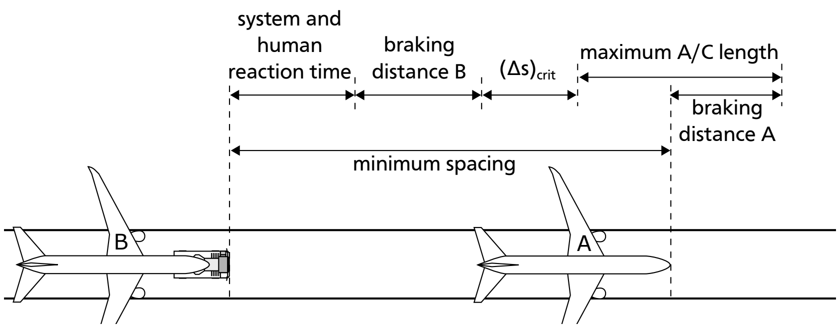


Figure 3.7.: Graphical derivation of critical position error $(\Delta s)_{crit}$ (illustrated by author incorporating reference distances of [Int04, pp. 3-10,3-11,4-2,4-3])

The calculation with considered safety margins and reaction times is outlined in Appendix B.

3.3.2 Human-Automation Requirements

As visualized in Figure 3.5 and Figure 3.6, acceleration and deceleration shall be automated while braking and steering can still be applied manually. Hence, the speed control in particular requires human-automation cooperation. Figure 3.8 visualizes the proposed interaction between human, automation, and the supporting HMI.

According to European Aviation Safety Agency (EASA), the pilot must be in control of the aircraft movement while taxiing [Eur12]. As long as no new regulations transfer this responsibility from the pilot to further instances, the automation may

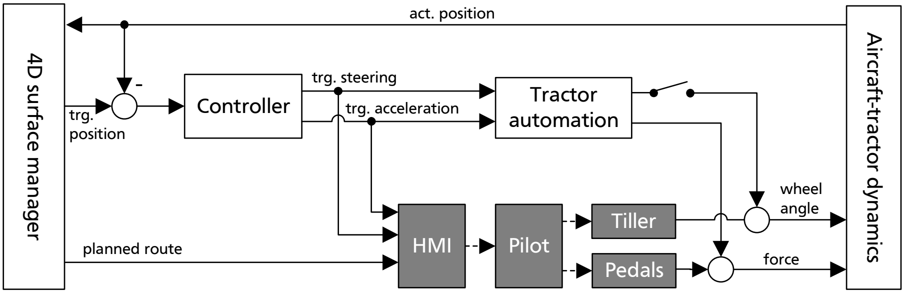


Figure 3.8.: Simplified overview of the automation control loop with pilot and HMI integration

support the pilot but has to allow for an overruling interference at any time. As a consequence, pilots' traffic awareness needs to be maintained. Referring to the main issues of general situation awareness with automated systems involved, pilots need to be kept inside-the-loop (see Section 2.2.4). Thus, the system design shall increase vigilance and reduce complacency as well as the amount of passive processing [EBJ03]. Moreover, the system has to provide helpful feedback [EBJ03]. Further improvement of situation and traffic awareness can be reached by developing an easily understandable logic and HMI [EBJ03]. When the pilot fully understands the system, she or he is able to better comprehend her or his own role and receive guidance instructions faster. Resulting reduced head-down times support the traffic awareness of the pilots.

In preliminary discussions, airline pilots confirmed these requirements by stating the importance of retaining full control and of being kept inside-the-loop. Subjective usability and acceptance, which do not only depend on a high degree of situation and traffic awareness, can additionally be supported by comprehensive user integration during HMI development. In order to meet the requirements of the specific user group of airline pilots, a user-centered design approach is suggested. An overview of performance and human-automation requirements is depicted in Figure 3.9.

3.3.3 Human-Machine Interface Requirements

In the procedure definitions in Figure 3.3 and Appendix C, pilot tasks requiring HMI support are highlighted by rectangular boxes on the top-right of the corresponding tasks. These functions, complemented with functions resulting from the scenario

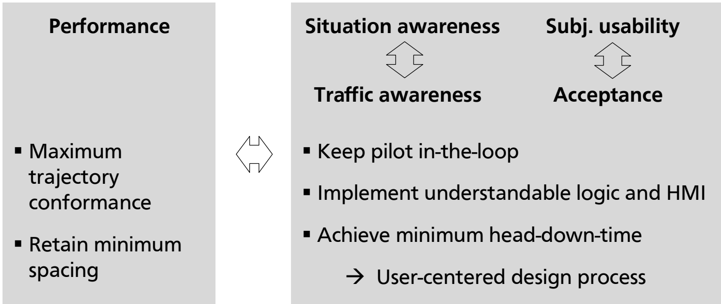


Figure 3.9.: Summary of performance and human-automation requirements for the concept development

description, are summarized in Table 3.3. In the center column, the automation modes are listed, indicating whether each function has informative or guidance characteristics. On the right, a clustering into four functional groups is conducted. The main premise when determining the use of an EFB for the current TBDT concept is that the HMI design shall describe an extension of existing EFB applications by adding necessary functions, without a fundamental rebuild. Consequently, the main part of the EFB during taxiing, which is the airport moving map (AMM), shall remain in the center of attention. Only functions, which cannot be included in the map are presented in separated functional display areas.

Functions suitable for presentation on an AMM are mostly for the purpose of information. With respect to the modes TBDT I and II, which consider manual steering, the target route visualization has a guidance function and the pilots will not receive further routing information via additional channels. The trajectory conformance indicator shall provide an indication about the actual trajectory conformance and possible interference recommendations. In the modes TBDT I and III, the trajectory conformance indicator serves as guidance regarding possible pilot brake input. In modes TBDT II and IV braking shall be automated, and the conformance indication is for information only. This indicator can be integrated into the AMM (similar to the taxi navigation display (TND) in Section 2.1.2) as well into a separate speed indicator area on the screen (similar to the advanced primary flight display (PFD) in Section 2.1.2). Further information about the actual state of the aircraft-tractor combination can be included into a separate progress bar while additional, individual action recommendations may be communicated via a free text field.

Table 3.3.: Required functions of HMI and categorization

Function	Mode-specific informative (I) or guidance (G) characteristics: TBDT I	TBDT II	TBDT III	TBDT IV	Functional display area: AMM	Speed indicator	Progress bar	Free text field
Surrounding traffic	I	I	I	I	•			
Airport layout	I	I	I	I	•			
Ownship position	I	I	I	I	•			
Tractor-aircraft connection state	I	I	I	I			•	
Cleared and un-cleared route sections	I	I	I	I	•			
Progress indicator	I	I	I	I			•	
Target route	G	G	I	I	•			
Trajectory conformance indicator	G	I	G	I	•	•		
Advice to set/release park brake	G	G	G	G				•
Advice for engine start	G	G	G	G				•

The graphical implementation of the required functions need to be in line with the user-oriented design principles listed in Section 2.2.1. The principle of *appropriateness* mainly suggests to only present information and guidance relevant for the current task. In order to generate a *self-descriptive* design, recommendations for user intervention need to be clearly identifiable. The *conformance with expectations* can be maintained by the adherence of common nomenclature, symbols, and color codes as summarized by Yeh et al. [Yeh+16]. *Learning support* can be enhanced by taking the previous principles into consideration. Furthermore, the professional context of use allows for individual user trainings. The principles *controllability* and *fault tolerance* can be neglected as the HMI mostly serves as an output device, not allowing the pilots to modify the general taxi process. *Suitability for customization* is a principle which will not be taken into consideration, as aviation systems and procedures are mostly standardized and not available for individual adjustments.

3.4 Trajectory Control Concept

In accordance with Figure 3.8, the 4D-SMAN forms the outer control loop by generating a set of target trajectories for all taxiing aircraft and by monitoring their conformance. A recalculation will be triggered only in case of large deviations affecting the trajectories of other aircraft. The 4D-SMAN considers both short-term as well as long-term conflict detection and resolution. While the long-term detection enables an optimized recalculation of the complete set of trajectories, short-term functions focus on the affected aircraft only [BFH11]. Concepts of the outer control loop are not limited to TBDT and are investigated in several studies focusing on trajectory generation (e.g. [Re17; Swe+07; GT12; LSB10]) and conflict resolution (e.g. [BFH11; GT12]). Additionally, in every automation mode of TBDT the pilot is responsible to apply brakes or tiller in order to avoid safety critical conflicts.

The on-board inner loop has the objective to maneuver the tractor-aircraft combination in line with the trajectory and therefore needs to be defined for the specific use case of TBDT. The inner controller applies a longitudinal force to the aircraft and causes a deflection of the tractor wheels. Depending of the automation mode, the applied force is the sum of the acceleration and deceleration of the tractor and the manually or automatically engaged main gear brakes. The deflection of the tractor wheels can be triggered by either the tractor automation or manual steering input of the pilot. Regardless of the actual automation mode, the pilots shall always be able to overrule potential automated input by manually applying brakes or tiller. A possible implementation of the inner control loop under idealized circumstances is included in the description of the simulator setup in Section 4.2. The following explanation sets the basic principles for the target trajectory design.

Even though the 4D-SMAN is not developed in this study, the basic characteristics of the target trajectory need to be defined consistent with the execution concept. The longitudinal attributes of the target trajectories are summarized in Figure 3.10. The speed profile shall be composed of both segments with constant speed, and segments with constant accelerations or decelerations. In order to ensure the tractor generates sufficient acceleration on light slopes, the target acceleration is limited to $a_{max} = 0.15\,\frac{\mathrm{m}}{\mathrm{s}^2}$. Standard decelerations which require no main gear braking support are limited to $a_{min} = -0.4\,\frac{\mathrm{m}}{\mathrm{s}^2}$, while harsh brake-supported decelerations shall not be below $a_{min,BRK} = -1.2\,\frac{\mathrm{m}}{\mathrm{s}^2}$. The latter maximum deceleration is considered to be reasonable for acceptable passenger comfort as related studies define maximums between $-1.0\,\frac{\mathrm{m}}{\mathrm{s}^2}$ and $-2.4\,\frac{\mathrm{m}}{\mathrm{s}^2}$ (e.g. [CSF01, p. 42; CS11, p. 2236; Bak+11, p. 2])[1]. Target taxi speeds on straight taxiway segments are set to $GS_{trg} = 23\,\mathrm{kn}$ ($11.8\,\frac{\mathrm{m}}{\mathrm{s}}$), which is 5 % above the current maximum TaxiBot speed. During turns, the speed is set according to ICAO advice [Int04, p. 3-15] and common airline policies to $GS_{trg,turn} = 10\,\mathrm{kn}$ ($5.1\,\frac{\mathrm{m}}{\mathrm{s}}$).

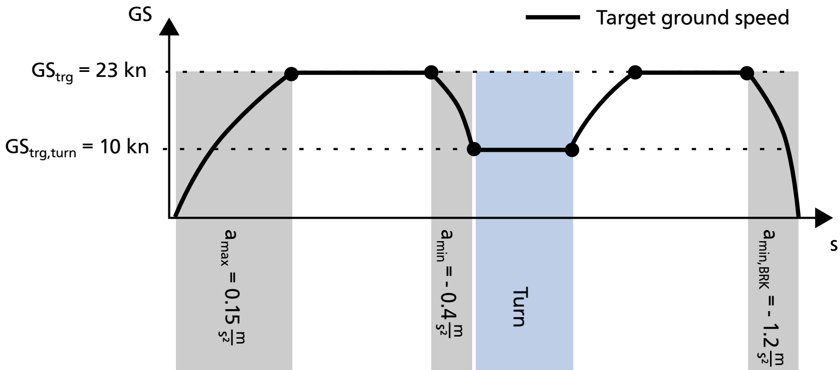


Figure 3.10.: Longitudinal ground speed (GS) constraints for trajectory generation

While Figure 3.10 describes the speed principles for the target trajectory, manual braking modes may result in increased deviations. When the pilot applies fewer deceleration via brakes than intended by the target speed profile, the following target speeds need to be reduced in order to apply further deceleration. Similarly, when the pilot brakes harsher than intended, or brakes when no deceleration is required, the tractor needs to tow the aircraft at higher speed than initially planned. For the latter case, maximum speeds for all taxiways need to be defined. Figure 3.11

[1] Maintaining passenger comfort is the premise for maximum planned decelerations. This does not preclude the realization of higher decelerations in unplanned situations.

shows a situation in the proximity of a turn. Even though the target speed is not reduced, the pilot activates the brakes. As soon as the pilot releases the brakes, the resulting position deviation is counteracted by acceleration of the tractor. As the target position is ahead of the actual position, the tractor drives faster than initially planned by not exceeding the individual maximum speeds at the current position. With this logic, it can be assured that the controller straightens out inaccurate pilot input while simultaneously ensuring that maximum speeds (e.g. in turns) will not be exceeded.

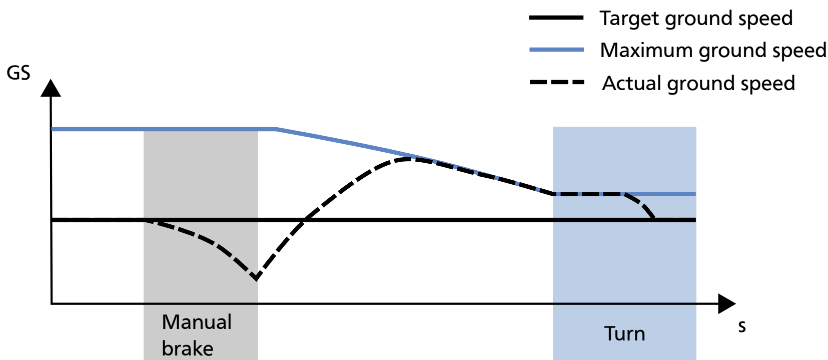


Figure 3.11.: Longitudinal ground speed set by tractor's control loop after manual braking input

The lateral trajectory profiles shall be composed of straight segments and continuous curvature clothoids during turns. Instead of circular arcs, clothoids allow for a smooth transition between straight segments and turns, as the nose gear (or tractor wheel) angle does not exhibit discontinuity [SS90]. An exemplary lateral profile is shown in Figure 3.12.

3.5 Human-Machine Interface Concept

The HMI design process according to DIN EN ISO 9241-210 is highlighted in gray in Figure 3.1. The applied user-centered design process describes an iterative approach. With regard to the Cockpit HMI supporting the pilot during TBDT, two major evaluation iterations lead to a prototypical design. The following sections explain the evaluations, composed of pilot interviews and pre-trials in a flight research simulator.

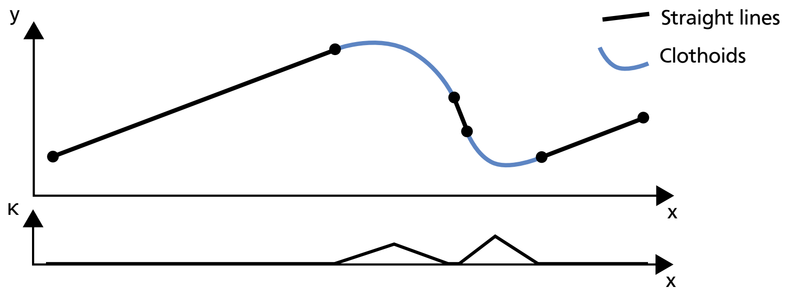


Figure 3.12.: Lateral route profile and curvature concept for trajectory generation

3.5.1 Expert Interviews

In consideration of the design principles stated in DIN EN ISO 9241-110, several designs for individual functions were developed, serving as input for five structured pilot interviews.[2]

Five pilots participated in the expert interviews, with a duration of approximately 90 min each. Appendix D provides details on the participating pilots. The interviews are structured into two main parts.

After the presentation of the general purpose of research, the first part deals with specific HMI functions as summarized in Table 3.3. The pilots were asked about possible visualizations for each function. Their proposals were captured by means of notes and individual sketches of the ideas. Hereafter, different prepared design proposals were presented to the pilots. Within subsequent discussion for each function, the design proposals and the individual pilot concepts were ranked.

The second part of the interviews covered general positioning and allocation of the specified functions on an imaginary screen surface. The interactive process provided insight into how functions should be clustered and organized on the EFB screen.

The outcome of the interviews demonstrates that the participating pilots fully understand the TBDT concept and the related interaction between human and automation. Furthermore, they appreciate the use of an EFB as a supporting device. Simultaneously, they highlighted the importance of an easily perceivable design, as the EFB might be positioned outside the pilot's primary field of view. Even though the participants proposed various positioning concepts of the elements on

[2] A detailed presentation of the interviews is provided by Pflanzl as well as by Bernatzky, Baumann, and Klingauf [Pfl15; BBK16].

the screen, they confirmed the necessity for four functional display areas, as reflected in Table 3.3.

Figure 3.13 presents the function allocation which fits best to the interview results. Besides the importance of prominently positioning the AMM, the pilots stated the need for an indicator of the actual process step in the unfamiliar taxi procedure.

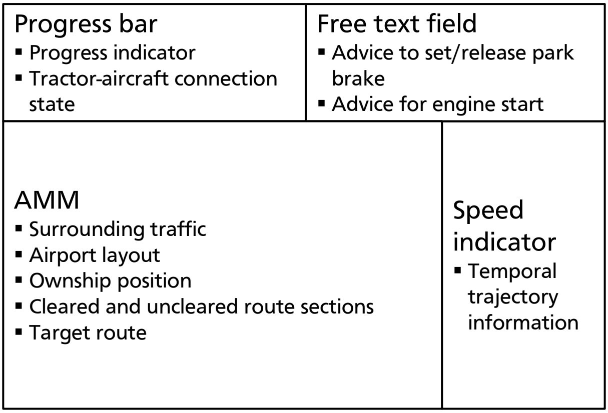


Figure 3.13.: Function allocation on the EFB screen based on the outcome of the pilot interviews

With regard to the individual functions, the pilots were in favor of a well-known symbolism in line with current cockpit designs. For the introduction of new icons, supportive text elements were proposed.

Concerning the AMM, several enhancements were demanded by the participants. In the consecutive development of the AMM, their ideas were only included if relevant for TBDT.

The speed indicator was the most discussed interface component. The design proposals show a high amount of variety. For several participants, it was difficult to distinguish between information and guidance, especially in a case of switched automation modes. Consequently, the final design should clearly state when pilot intervention (e.g. braking) is required. The most promising pilot proposal was similar to the design of the PFD speed scale, as also proposed by Foyle et al. [Foy+11] (see Figure 2.3). The integration of speed information into the AMM was discussed critically, as the EFB position is located at the outer margin of the pilots' field of view, demanding a clear, large, and independent speed advisor.

The results of the interview allow for the definition of the basic design and function allocation, whilst the speed indicator needs to be further assessed.

3.5.2 Pre-Evaluation of the Speed Indicator Function

The basic control concept of Figure 3.8 points out the cooperation of pilot and automation when realizing the deceleration force. The total force is the sum of the forces applied by the tractor and the main gear. In TBDT I and III, the aircraft brakes shall be applied manually, causing a direct interaction between automation and human action. This strengthens the importance of a proper speed indicator on the EFB. As the final simulator evaluation focuses on the variation of automation modes (see. Figure 3.6), findings should not be affected by an unsuitable speed indicator. Therefore, a pre-evaluation retaining one automation mode but varying different speed indicator designs was conducted.

3.5.2.1 Concept Design

Four speed indicator concepts were developed based on the findings of the pilot interviews, general design considerations, and different presentation principles. The design procedure, described by Kemmerzell [Kem16], results in one acoustic and three visual designs. As shown in Figure 3.14, each concept combines an analog and a digital component. The main objective of the digital advice, realized by a visual *BRAKE* command (in concepts B to D) or a voice appearance (in Concept A), is to obtain the pilot's attention and to highlight the need for manual intervention.

The analog part provides additional information about the required amount of brake input and differs among the concepts A to D. The following overview provides a brief explanation of each design:

- **HMI Concept A – Voice Command**
  The first concept is in line with present-day taxi operations. Accordingly, the controllers provide all guidance instructions via radio without any EFB visualization. As long as no braking action is required, pilots will hear no speed-related instructions. In case of harsh decelerations ahead, the controllers communicate the next target speed without any information about the required deceleration. No feedback regarding the conformance of the actual with the planned deceleration is provided. The use of an automatic synthetic voice for instructions is conceivable in order to keep the workload of the controller to an appropriate amount. Since the individual target speed should be

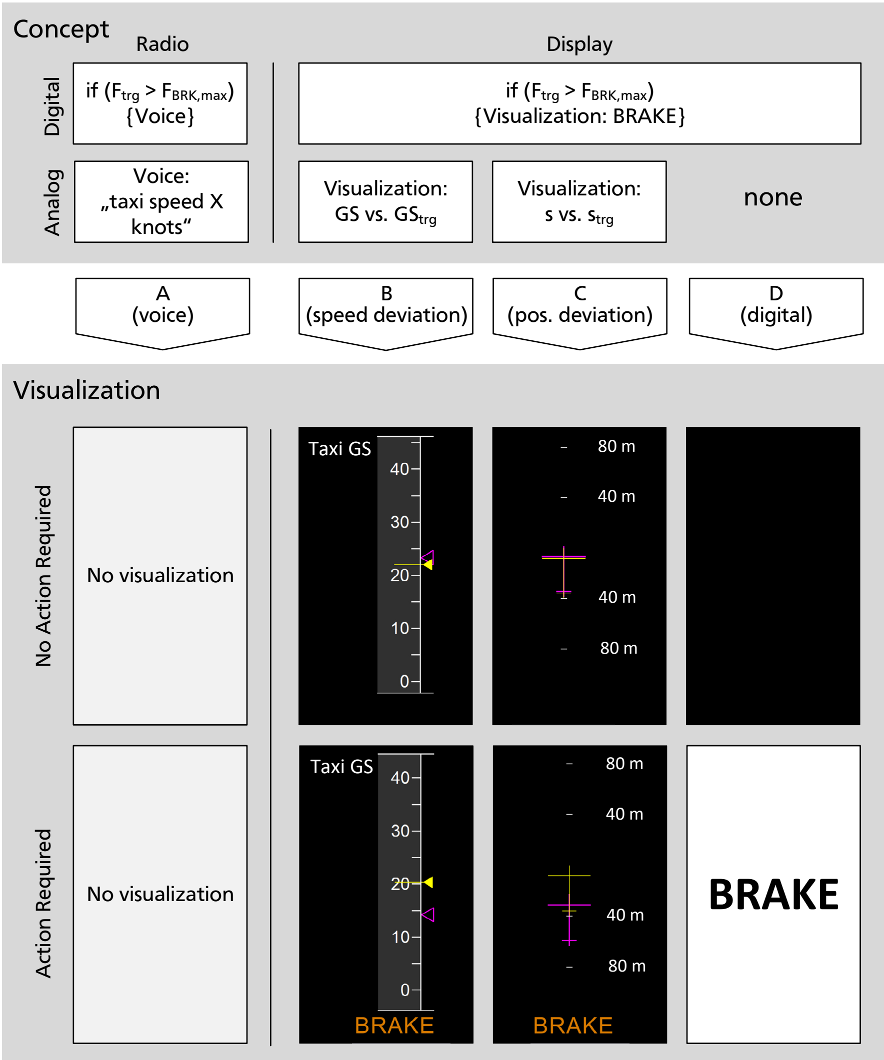


Figure 3.14.: Comparison of evaluated speed indicator concepts of the pre-evaluation (illustrated by author analog to [Ber+17], visual concepts designed in [Kem16])

communicated to the affected aircraft only, the communication architecture (party-line) needs to be revised.

- **HMI Concept B – Visual Speed Comparison**
  Concept B, which is similar to the modified PFD of Foyle et al. [Foy+11], visualizes a dynamic speed scale on the EFB. In contrast to conventional PFDs, the magenta target speed marker moves dynamically and the scale is expanded to begin at 0 kn. Small deviations between actual (yellow) and target (magenta) speed will cause the on-board controller of the tractor to accelerate or decelerate. When decelerations require pilot support, the difference between the two markers increase and an additional *BRAKE* advice clarifies the demand for manual intervention.

- **HMI Concept C – Visual Position Comparison**
  The target speed of concept B is a function of the longitudinal deviation between actual and target position. Concept C directly visualizes this position deviation by presenting two aircraft symbols (true to scale). Similar to the previous concept, the target position is marked magenta while the actual position is presented by means of a yellow aircraft symbol. The need for manual brake input becomes apparent by an increased distance between the aircraft symbols supported by the textual *BRAKE* advice.

- **HMI Concept D – Visual Digital Advice**
  The last concept does not include any analog information. As the advice for braking is communicated by text only, a larger screen area is suggested for the text. The advice appears when braking is required and disappears when the position deviation is reduced to a given tolerance which can be controlled automatically by the tractor. To further support the attention-grabbing characteristic, the screen color changes from black to white when the advice appears. With this implementation, concept D provides the minimum required information that can be easily perceived, even though the EFB is placed at the outer margin of the pilot's field of view.

3.5.2.2 Evaluation Design and Results

The pre-evaluation took place in the flight research simulator D-AERO of the Institute of Flight Systems and Automatic Control (FSR) of TU Darmstadt, simulating a medium-haul narrow-body aircraft. In total, five pilots – three active airline pilots and two trained pilots without line experience – participated in the trials. More detailed information on the participants can be found in Appendix E.

Each session lasted for about 150 min and was divided into a welcome briefing explaining the concept as well as the upcoming task, the simulator trials, and a debriefing with open discussion. In a within-subject design, every pilot participated in four evaluation runs testing all four implementations of the speed indicator. The chosen automation mode TBDT I was not changed during the trials, which means that in every run pilots needed to steer manually and brake according to the speed advisor. One initial practice run allowed the pilots to test the different designs and to get used to the simulator environment.

All runs were placed on the same route in a simulated environment of Frankfurt Airport. While the route was not changed between the individual runs, three deceleration segments requiring manual brake input were randomly spread along the route. An exemplary speed profile and the static route along taxiway N is illustrated in Figure 3.15.

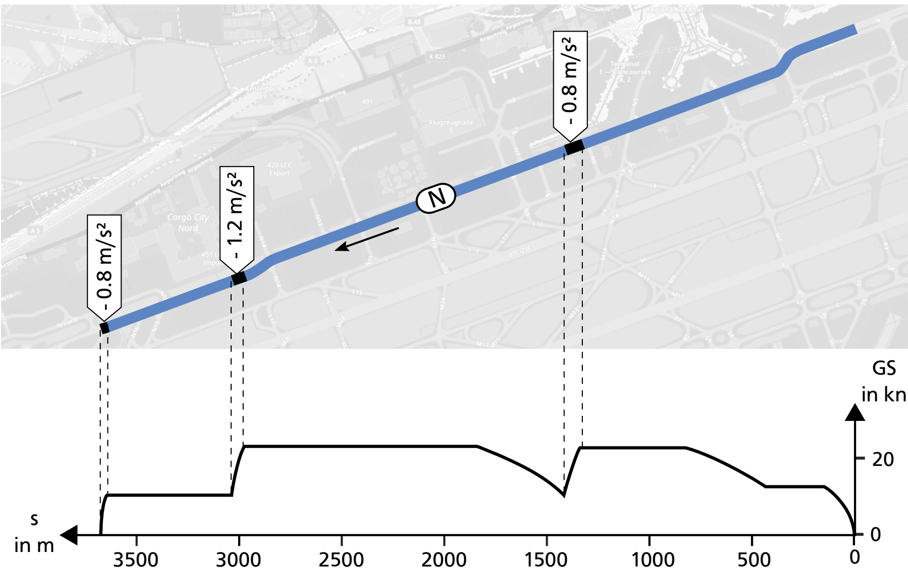


Figure 3.15.: Route and ground speed profile of pre-evaluation trajectory (map data copyrighted by OpenStreetMap contributors available from https://www.openstreetmap.org)

In addition to open feedback, the participating pilots were asked to answer German questionnaires of the System Usability Scale (SUS), NASA Raw Task Load

Index (RTLX), and Situation Awareness Rating Technique (SART). The SUS is introduced in Section 2.2.3 and consists of ten Likert scale questions. The RTLX is an unweighted version of the conventional NASA Task Load Index (TLX), which captures the subjective workload [NAS11; BBH89]. Six individual workload related questions need to be rated on scale between 0 and 20 [NAS11]. Subjective situation awareness was assessed by the SART, which includes ten questions of the categories *demand*, *supply*, and *understanding* to be rated on a scale between 1 and 7 [STK91].

In addition to the subjective questionnaires, the measured time between the appearance of the *BRAKE* advice and the first pedal movement serves as an objective performance measurement. The metrics of the pre-trials are summarized in Table 3.4.

Table 3.4.: Metrics during the pre-evaluation of different speed indicator designs

Metric	Applied technique	Characteristic
User satisfaction	SUS	subjective
Situation awareness	SART	subjective
Workload	NASA RTLX	subjective
Performance	reaction time: length of time interval between *BRAKE* advice and first pedal movement	objective
Personal preference	open questions regarding HMI concepts and TBDT concept	subjective

Due to the number of five participating pilots, the measured data regarding user satisfaction, situation awareness, workload and performance do not allow for any statistical tests. Consequently, the following findings are analyzed qualitatively by discussing the means and standard deviations. Even though no statistical relevance can be derived, the analysis of the open pilot feedback and discussion support the observed trends and provide reasonable explanations.

With respect to the reaction time, which is presented in Figure 3.16, the HMI concepts A and D are rated best. These two concepts are characterized by comparatively simple logic with minimal information. The reaction time of concept A includes both the instructor's reaction time as well as the duration of the announcement. Hence, if the audio advice can be automated and shortened, reaction times will be even lower. The concepts B and C, which provide additional information concerning speed or position deviation, show mean reaction times above 3 s. Concept C further reveals the highest deviations, implying that the performance of concept C is highly dependent on the individual pilot.

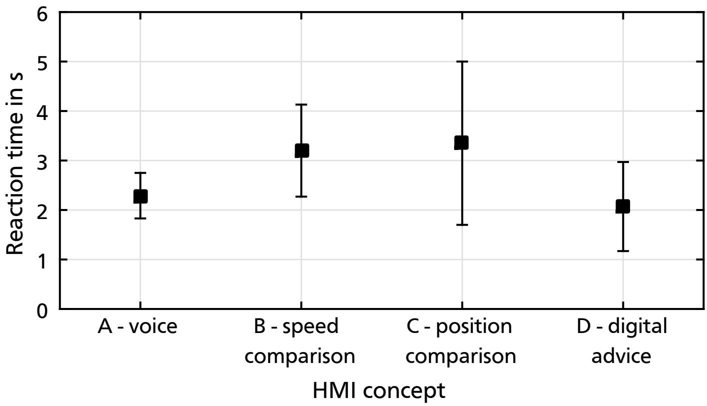


Figure 3.16.: Mean values and standard deviation of the measured reaction times during the pre-evaluation of different speed indicator designs

In Figure 3.17, the subjective workload measurement in terms of the RTLX is depicted. Due to a high variation, all standard deviations exceed the differences between the individual means. Still, the same trend as with the measured reaction times can be observed, and the rather simple HMI concepts A and D result in comparatively low subjective workloads. Concept B and C, providing additional information about the required decelerations rates, seem to cause a higher workload.

Focusing on the subjective situation awareness, the SART findings in Figure 3.18 suggest only few differences of the means. Compared to concepts A, B, and C, the digital concept D provides the fewest amount of information. The discussion in the trials revealed that the pilots' awareness of the trajectory was experienced to be rather low in concept D. This perception is supported by the measured mean values of the SART rating.

According to Figure 3.19, all mean SUS scores are above the value of 75. Applying the adjective rating proposed by Bangor, Kortum, and Miller [BKM09], all systems would be rated *good* to *excellent*. When comparing the individual means, the acoustic concept A receives the highest rating. Among the visual concepts, the comparison of actual and target speed (concept B) is rated best.

Regarding the visual concepts (B, C, and D), concept B receives best SUS and SART scores. This can be seen in line with the feedback of the pilots, emphasizing

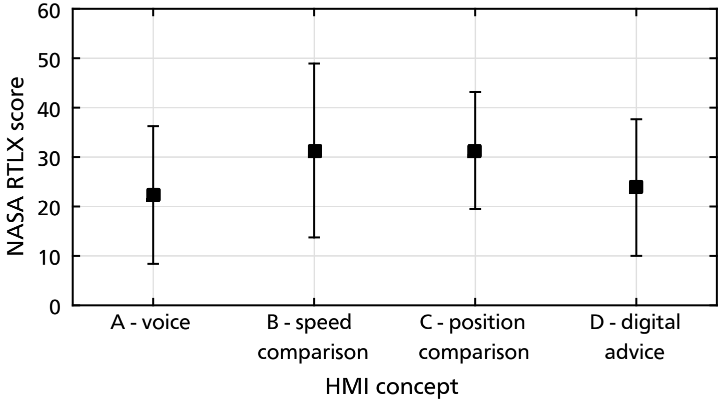


Figure 3.17.: Mean values and standard deviation of the subjective workload during the pre-evaluation of different speed indicator designs

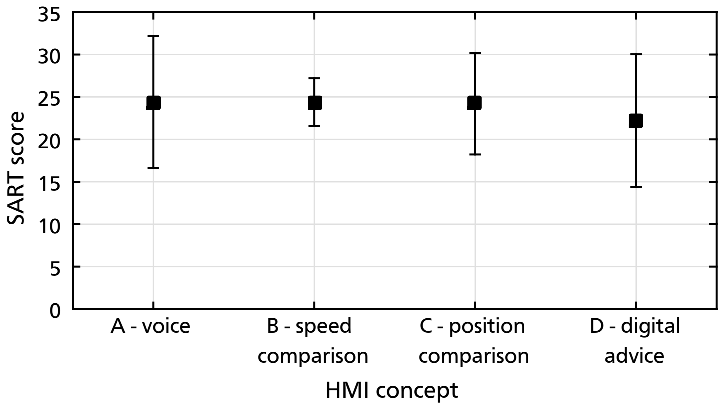


Figure 3.18.: Mean values and standard deviation of the subjective situation awareness during the pre-evaluation of different speed indicator designs

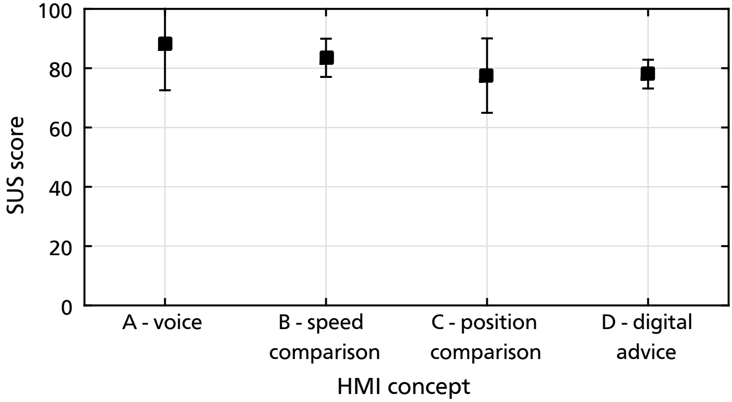


Figure 3.19.: Mean values and standard deviation of the user satisfaction during the pre-evaluation of different speed indicator designs

the intuitiveness of braking according to a presented speed deviation. In comparison to concept C, the participants preferred brake guidance on the basis of a speed deviation rather than of a position deviation. This impression is supported by the consideration of the required mental conversion between position, speed, and deceleration, as outlined in Figure 3.20 (one versus two integrations).

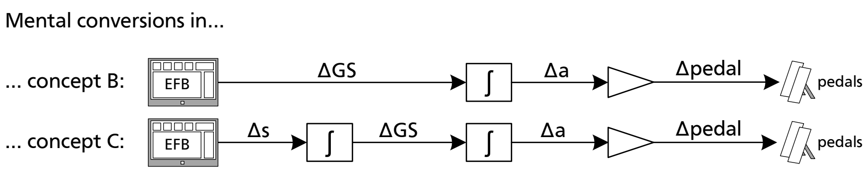


Figure 3.20.: Comparison of HMI concepts B and C regarding required mental transformation steps between EFB output and pedal input

Although concept B is considered to be more intuitive and to provide helpful information, the measured reaction time and workload is best for concepts A and D. The main advantages of these two concepts are simplicity and the attention-grabbing characteristics.

As a consequence, a revised concept needs to combine the visualization of the actual speed deviation with an attention-grabbing behavior (extensive color change and/or acoustic signal). Comparing the recommendation with the design principles of DIN EN ISO 9241-110 (see Section 2.2.1 and [DIN08]), pilots seem to attach great importance to the *conformance with expectations* by preferring an orientation on the PFD speed scale. Moreover, the requested way of presenting the information corresponds with the principle of *appropriateness regarding the task*.

3.5.3 Completion of Human-Machine Interface Design

Following the findings of the pre-evaluation, four major requirements concerning the visual speed indicator need to be met:

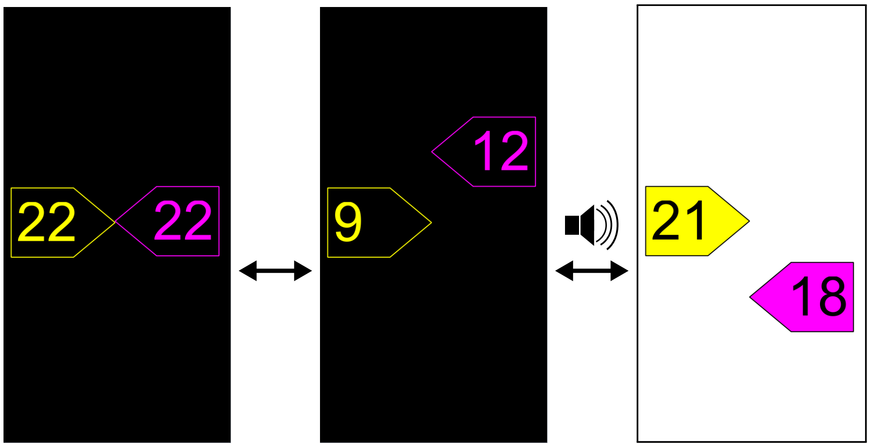
- The visual speed indicator shall include an "eye-catching" element occurring when brake input is required.
- The amount of required brake input shall be transmitted by means of a speed deviation.
- The visual speed indicator shall provide feedback allowing for an adjustment of brake intensity.
- The symbolism of the visual speed indicator shall be aligned with common cockpit displays.

The amount of information a person can process simultaneously depends on the modality. It is generally easier to handle information of different types – like visual and auditory – than receiving information only via one sensory channel [WH00]. This assumption was also confirmed by pilots stating the difficulty of simultaneously observing the traffic situation and watching out for temporal speed instructions on the EFB in the pre-evaluations. Even the simplest graphical design (concept D) leads to a subjective reduction of traffic awareness. According to the findings, an acoustic signal indicating manual brake phases has been included into the final design concept.

When the trajectory control algorithm calculates higher deceleration rates than the tractor can apply on its own, a sound signal notifies the pilot. The signal shall lead to fewer distractions, since the pilot can fully concentrate on monitoring the outside situation and only needs to observe the EFB when advised via the acoustic channel.[3]

[3] The inclusion of acoustical trajectory guidance is also advised by ICAO in its Aviation System Block Upgrade definition [Int16d].

In order to provide both high trajectory awareness and user satisfaction, the acoustic signal is supplemented by a novel visual speed indicator design inspired by concept B. In contrast to the design tested in the pre-evaluation, the final design uses a simplified symbolism of two maximized markers indicating actual and target speed. Figure 3.21 illustrates the constant appearance of both speeds. As long as no pilot intervention is required, the background is black. When manual braking is required, the sound signal is complemented by the background turning white. The use of large symbols and the elimination of the speed scale facilitate a simple design, quickly perceivable after being refocused.



No manual braking required
$|F_{trg}| \leq F_{tr,max}$

No manual braking required
$F_{trg} > F_{tr,max}$

Manual braking required
$F_{trg} < (-F_{tr,max})$

Figure 3.21.: Final design of speed indicator

The final HMI design combines the resulting speed indicator with the other functions, summarized in Figure 3.13. In accordance with the premise of developing an HMI design that can be integrated into existing EFB applications, four functional modules are proposed. In the bottom-left of Figure 3.22, a state-of-the-art AMM fills the largest area of the screen. In addition to common functions, like the visualization of taxiways and the ownship position, the taxi route, with a distinction between cleared and uncleared sections, shall be included. The progress bar (top-left in Figure 3.22) shall provide orientation regarding both the current process step and the tractor-aircraft connection state. Newly developed and uncommon symbols are supported by text. If included into current EFB applications, the visualization of the additional TBDT steps can be integrated into existing progress visualization concepts. According to the TBDT concept, all radio communication with ATC shall be replaced with automation and textual advice. As a great variety of possible instructions and requests exists, a free text area on the top-right shall serve as a platform for temporal information and instructions while concurrently enabling pilot input (e.g. accept or decline trajectory).

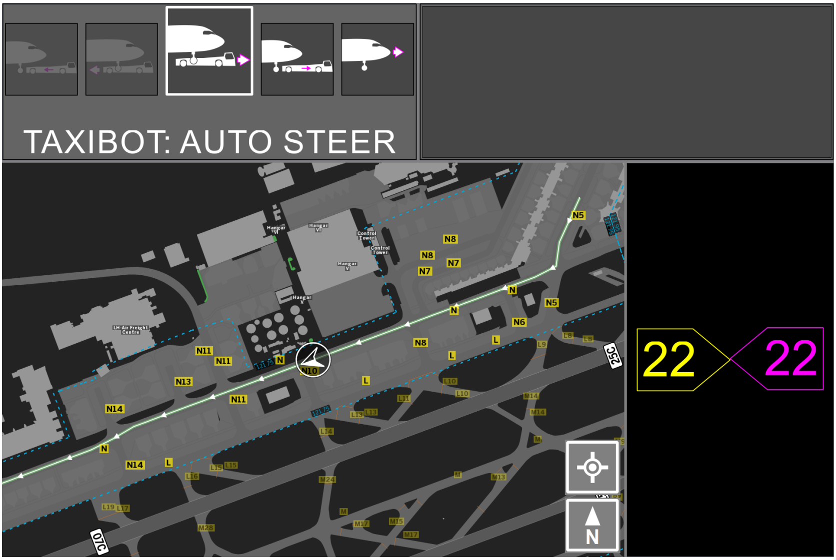


Figure 3.22.: Final design of the proposed EFB application

The proposed EFB design along with the scenario description, the formulation of automation modes, and the definition of the trajectory control logic set the basis of this study and the foundation for hypotheses formulation.

3.6 Hypotheses Formulation and Measurements

The global hypothesis formulated in Section 2.3 anticipates that pilots can be integrated into TBDT with acceptable performance and, compared to RBTO, with unchanging or increasing traffic awareness, user satisfaction, and acceptance. The developed concept described in the current chapter has the objective of meeting the requirements resulting from the global hypothesis. The pilot interviews and the pre-evaluation in the flight research simulator as well as the literature review concerning STBO evaluations lead to four main hypotheses.

In line with the global hypothesis, the main hypotheses refer to performance (Hypothesis 1), traffic awareness (Hypothesis 2), user satisfaction (Hypothesis 3), and acceptance (Hypothesis 4) of pilots. Each main hypothesis is further divided into several sub hypotheses.

As categorized in Table 3.5, sub hypotheses comparing the trajectory-based modes TBDT I to IV address the independent variables *braking* and *steering*. The difference between RBTO and the TBDT modes is not limited to *braking* and *steering* but is characterized by several changing variables (e.g. engine start, guidance principles, or target times), which do not allow for isolated consideration. Consequently, comparisons with RBTO are carried out on a higher level with *automation mode* as the independent variable.

Table 3.5.: Summary of hypotheses formulated in this chapter and assignment to automation modes

Main hypothesis	**Sub hypotheses**	**Compared modes**	**Independent variables**
1 Performance	1.1, 1.2, 1.3	TBDT I-IV	braking, steering
2 Traffic awareness	2.1, 2.2 2.3	TBDT I-IV RBTO, TBDT I-IV	braking, steering automation mode
3 User satisfaction	3.1, 3.2 3.3	TBDT I-IV RBTO, TBDT I-IV	braking, steering automation mode
4 Acceptance	4.1	not mode-specific	speed changes, steering

3.6.1 Expected Performance (Hypothesis 1)

In Section 3.3.1, the longitudinal position error is introduced as the main performance measurement for trajectory conformance. Although the lateral deviation between actual and target position is also a safety critical variable, it is not essential for meeting the target velocity profile. Consequently, the term *trajectory error* is defined as the arc length along the trajectory between the target position and the nearest position to the nose wheel on the target route (see Δs in Figure 4.3). The trajectory error serves as an indicator to evaluate the effect of the different

TBDT modes on the performance. Since conventional RBTO do not include time constraints, Hypothesis 1 only considers the modes TBDT I to IV.

Hypotheses 1.1 and 1.2 focus on the effect of automated control input on the trajectory error. Hypothesis 1.1 refers to the brake automation and expects the trajectory error to be higher when braking is applied manually. During manual braking, the pilot shall react to the speed indicator and she or he will not be able to apply the brakes earlier than the automation would. Even though Hypothesis 1.1 may be considered trivial, it has been formulated for verifying the speed automation control and for reasons of completeness.

With respect to steering, no direct connection between steering and the trajectory error exists. As automated steering reduces the amount of concurrent tasks for the pilot, the level of arousal is expected to decrease. Visualizing the Yerkes-Dodson law in Figure 3.23 shows that performance is best at a specific level of arousal and decreases for over- or under-arousal [Coh11, p. 2737]. As during the pre-evaluation, all measured RTLX ratings are low,[4] a corresponding low level of arousal is assumed. Thus, in Figure 3.23, the TBDT modes can be allocated prior to the optimum level of arousal and the automation of steering is expected to further reduce performance (Hypothesis 1.2).

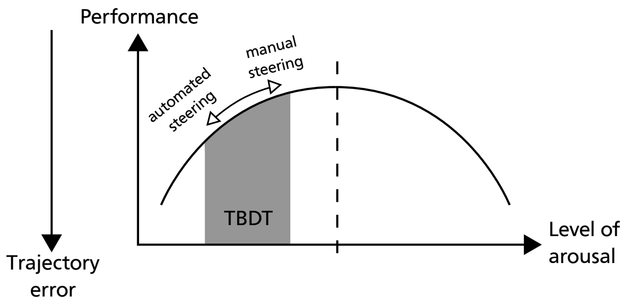


Figure 3.23.: Visualization of Yerkes-Dodson law with expected reduced performance caused by automated steering during TBDT

According to the definition of the critical trajectory error defined in Section 3.3.1, Hypothesis 1.3 expects that the maximum trajectory error does not exceed the critical value. If the value is exceeded and the hypothesis needs to be rejected, the application of TBDT with conventional aircraft spacing (according to [Int04]) may lead to collisions.

4 According to Figure 3.17, all measured RTLX scores during the pre-evaluation are significantly below 50 % of the maximum achievable score.

Hypothesis 1.1: Automating aircraft brake input during TBDT results in a reduction of the lateral trajectory error.

Hypothesis 1.2: Automating steering input during TBDT results in an increase of the lateral trajectory error.

Hypothesis 1.3: The lateral trajectory error during TBDT I to IV is below $(\Delta s)_{crit} = 22\,\text{m}$.

For maintaining high trajectory conformance, pilots need to engage the brakes only when advised by the EFB. As a consequence, common brake input start after an increasing position deviation, causing the aircraft to be ahead of its target position (i.e. positive position error). An expected characteristic position error progress during manual brake phases equals Figure 3.24. Hypothesis 1 shall evaluate the pilot performance and thus focuses on the positive error caused by delayed brake input. Resulting negative errors are dependent on the tractor dynamics and the implemented control loop and thus not considered for testing Hypothesis 1.

Figure 3.24.: Common exemplary progress of the position error after manual brake input and visualization of investigated variables $(\Delta s)^+$ and $(\Delta s)_{max}$

On the contrary to the complete history of Δs, $(\Delta s)^+$ only considers positive deviations (aircraft ahead of target position), while the trajectory error measurement $(\Delta s)_{max}$ is the maximum positive trajectory error for each run (see Figure 3.24):

$$(\Delta s)^+ = \begin{cases} \Delta_s & \text{if } \Delta s > 0 \\ 0 & \text{if } \Delta s \leq 0\,, \end{cases} \tag{3.1}$$

$$(\Delta s)_{max} = max\left((\Delta s)^+\right)_{run}\ . \tag{3.2}$$

3.6.2 Expected Traffic Awareness (Hypothesis 2)

Regardless of the mode of automation, pilots need to maintain a high degree of traffic awareness when taxiing. Jones and Endsley investigated sources of situation awareness errors in aviation and found out that 76.3 % of situation awareness errors occurred at level 1 [JE96, p. 509]. In 35.1 % of all observed situation awareness errors, all relevant information was present, but the pilot was not able to perceive the relevant information while concentrating on other tasks [JE96, p. 509]. Endsley, Bolté, and Jones call this phenomenon of fixating on one aspect while neglecting others, attentional tunneling [EBJ03]. Regarding the situation awareness subset of traffic awareness on ground, level 1 comprises the perception of other aircraft, ground vehicles, and persons.

In particular during manual braking phases, the HMI implemented on the EFB calls for attention by a noise signal and a color change. This may lead to attentional tunneling. According to Wickens and Hollands, the attentional bottleneck especially occurs when relevant information is transmitted via the same channel [WH00]. Therefore, providing (visual) speed information may negatively influence the (visual) perception of the surrounding traffic. The simulator evaluation shall investigate if the perception of the environment is disrupted by the developed HMI.

With regard to longer head-down times, as observed during previous studies of STBO concepts with modified primary displays (e.g. [Foy+11; Bak+15; BHF17]), an interaction between displayed information on the EFB and traffic awareness is expected. Less automation during TBDT requires a higher amount of guidance provided via the EFB. Thus, an increase of level 1 traffic awareness is expected when implementing automated braking or steering (Hypotheses 2.1 and 2.2).

In contrast to conventional RBTO procedures, TBDT I introduces additional constraints without offering automation support. Consequently, longer head down times are expected. TBDT IV automates all additional trajectory-related tasks without any remaining manual tasks relating to the maneuvering of aircraft. As a consequence, RBTO are expected to cause better traffic awareness than TBDT I but lower traffic awareness than TBDT IV do (Hypothesis 2.3).

Hypothesis 2.1: Automating aircraft brake input during TBDT results in an increase of the level 1 traffic awareness.

Hypothesis 2.2: Automating steering input during TBDT results in an increase of the level 1 traffic awareness.

> **Hypothesis 2.3:** The level 1 traffic awareness during RBTO is higher than during TBDT I (lowest level of automation) and lower than during TBDT IV (highest level of automation).

A common approach to measure traffic awareness is the tracking of eye movement and the calculation of eyes-out-the-window times. This procedure provides insight about how often the pilot monitors the outside situation. However, it does not directly assess how well external traffic is captured.

In order to provide a repeatable and comparable quantitative measurement directly related to the traffic perception, a modification of the external view in the simulator is required. As shown in Figure 3.25, external objects shall appear randomly along the planned route at randomly spread time intervals (also see Section 4.5.2).

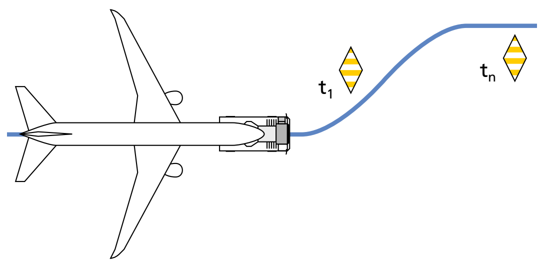


Figure 3.25.: Measurement concept for level 1 traffic awareness with external objects appearing along the target taxi route

Perceived objects need to be confirmed by the pilots of the simulator study via a hardware button. The mean reaction time between the appearances of objects and the manual confirmations of an individual run serves as a measurement for level 1 traffic awareness:

$$t_r = \frac{\sum_{i=1}^{n_{objects}} t_{r,i}}{n_{objects}}. \tag{3.3}$$

For the purpose of comparison, the unaffected reaction time for a setup without any parallel tasks was determined in a previous investigation. This study, involving 20 non-pilots, revealed a mean reaction time of $t_{r,unaffected} = 0.28\,\mathrm{s}$ (95 % confidence interval (CI) [0.25 s, 0.30 s]) when objects appear, filling the whole external view, and when no parallel tasks (e.g. taxiing or communicating) are present.[5] This comparison measurement provides knowledge about the general reaction time caused by the measurement technique itself.

3.6.3 Expected User Satisfaction (Hypothesis 3)

Besides performance, usability comprises the subjective satisfaction of the system user. The pre-evaluation and interviews revealed that pilots favor a clear distinction between automation and manual control. While all TBDT modes include automatic acceleration and deceleration to a given amount, the combination with manual braking or steering requires a human-automation cooperation. Furthermore, the potential loss of traffic awareness seems to be a major concern during previous discussions with pilots. These considerations lead to the Hypotheses 3.1 and 3.2, expecting the user satisfaction to be lower when TBDT tasks need to be conducted manually. Hypothesis 3.3 states that the conventional RBTO procedure is expected to obtain better user satisfaction than all TBDT modes. The main reason for this expectation originates in the general impression that pilots prefer to maintain full control and responsibility of the aircraft during taxiing, which can be guaranteed in RBTO only.

> **Hypothesis 3.1:** Automating aircraft brake input during TBDT results in an increase of the user satisfaction concerning the automation mode.

> **Hypothesis 3.2:** Automating steering input during TBDT results in an increase of the user satisfaction concerning the automation mode.

> **Hypothesis 3.3:** The user satisfaction concerning the automation mode during RBTO is higher than during all TBDT modes.

As introduced in Section 2.2.3, the SUS is a common measurement technique for comparing systems of the same context of use. The standard SUS questionnaire references its questions to the term *system*. In the final evaluation simulator setup, several conventional and innovative systems are present, including a novel EFB HMI, the standard cockpit devices and the simulated automated tractor. As the

[5] In the unaffected reaction time study, 20 researchers and students participated in a simulator study with hardware setup as in the main evaluation but with a limited external view. When no object was present, the external view was filled black. When the view turned white, the participants needed to push the hardware button. No further tasks had to be fulfilled.

evaluation shall provide insight about the effect of manual or automated braking and steering onto the user satisfaction, the term *system* was changed to *automation mode*.[6]

3.6.4 Expected Acceptance (Hypothesis 4)

In Hypothesis 3.3, RBTO is expected to obtain better SUS ratings than all TBDT modes. Nevertheless, the investigation of TBDT in this thesis is mainly motivated by the general performance enhancements enabled by trajectory-based taxiing (see Chapter 2). As a consequence, with Hypothesis 4 it shall be investigated if pilots are willing to hand over manual functions to automation even though their subjective user satisfaction may be lower. Possible reasons for doing so are the expected benefits regarding the TBDT goals of *safety*, *ecological efficiency*, and *time efficiency*, as identified in Section 1.4.

The aim of testing Hypothesis 4 is to determine if a correlation between the individual willingness to hand over a function to automation and corresponding expectations regarding the TBDT goals exists.

> **Hypothesis 4.1:** Pilots are willing to hand over manual tasks to automation if they expect benefits regarding safety, ecological efficiency, or time efficiency.

Having finished all runs in the main simulator evaluation, the participating pilots are asked to fill out an acceptance matrix as shown in Table 3.6. In the first part, the expected benefits regarding the TBDT goals of automated steering and braking shall be rated using Likert scales. The goal *time efficiency* is further divided into *taxi time reduction* and *predictability increase*. In the second part, the pilots are asked if they are generally willing to transfer steering or braking to automation.

6 In addition to the replacement of the term *system*, the modified SUS questionnaire was translated to German.

Table 3.6.: Questionnaire for the evaluation of the pilots' acceptance toward TBDT (translated from German)

I expect that automating the functions on the right is beneficial to the goals below.	Automatic steering	Automatic speed changes
Safety enhancement	☐☐☐☐☐	☐☐☐☐☐
Ecological efficiency enhancement	☐☐☐☐☐	☐☐☐☐☐
Taxi time reduction	☐☐☐☐☐	☐☐☐☐☐
Predictability increase	☐☐☐☐☐	☐☐☐☐☐
	strongly agree … strongly disagree	strongly agree … strongly disagree

I am willing to hand over the functions on the right to automation.	Automatic steering	Automatic speed changes
	☐☐☐☐☐	☐☐☐☐☐
	strongly agree … strongly disagree	strongly agree … strongly disagree

4 Simulator Evaluation Setup and Procedure

The main simulator evaluation aiming at testing the hypotheses, formulated in Section 3.6, took place in the flight research simulator D-AERO of the Institute of Flight Systems and Automatic Control (FSR) at Technische Universität Darmstadt. This chapter provides a brief overview of the simulation environment and its adaptations for the concluding evaluation.

4.1 Soft- and Hardware Architecture

D-AERO is a fixed-base flight research simulator emulating an Airbus A320 aircraft. Developed and constructed at the FSR, the simulator has been used for a variety of evaluations mainly focusing on pilot integration into new operational scenarios (e.g. [Wes14; Urv14]). Providing a collimated visual system, D-AERO allows for profound research on human-machine interfaces (HMIs).

In order to obtain reliable results from the evaluation, the hardware components required for taxiing (tiller, pedals, and thrust lever) were revised. The pedals (brakes) and thrust lever needed to be adjusted in order to meet the behavior of an Airbus A320. Concerning the brakes, the integration of coil springs with a spring rate according to the reference plane enables realistic tactile feedback when applying the pedals. Furthermore, the snap-in positions of the thrust lever were customized to enable realistic behavior in the range between *ground idle* and *flight idle*. Besides the installation of the supporting electronic flight bag (EFB), no further hardware modifications were required.

On the contrary, several software components were developed allowing for the implementation of all trajectory-based dispatch towing (TBDT) modes, the integration of automatic measurements, and the visualization of a prototypical EFB application. The evaluation architecture, summarized in Figure 4.1, demonstrates the different modules and the main data exchange.

The simulator runs the commercially available software X-Plane 10 for generating the outer view and simulating the aircraft dynamics and kinematics in the trials. The A320 model is realized by means of an add-on from the company QPAC.

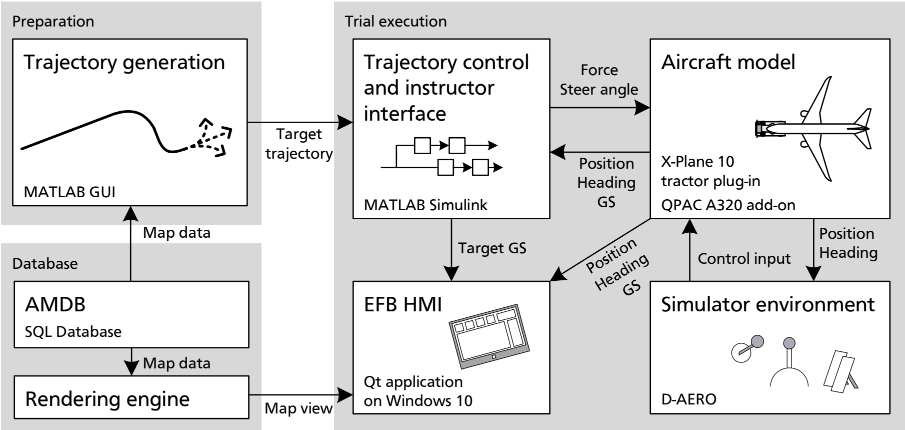


Figure 4.1.: Overview of soft- and hardware architecture and main data exchange

In addition to that, a developed tractor plug-in accelerates and steers the simulated tractor-aircraft system according to the external trajectory controller.

The automatic control loop is realized by data exchange between the modified X-Plane software and a controller implemented in MATLAB Simulink. The controller architecture is explained in Section 4.2. Repositioning of the aircraft, mode changes, route clearances, and data records can be triggered and controlled via an instructor interface of the Simulink model.

In the scenario description (see Section 3.2), the individual trajectories defining the target values for the controller are generated by a trajectory-based surface manager (4D-SMAN). As the simulator evaluation investigates the pilot integration by simulating a single aircraft only, the evaluation trajectories are generated individually by a trajectory generation tool realized in MATLAB. Target routing, speeds, and accelerations can be specified by the user while the actual properties of the route and the speed profile are consistent with the concept in Section 3.4. The outcome of the generator can be saved in matrices, containing time, position, distance, speed, acceleration, heading, and curvature as well as maximum speeds and accelerations with a resolution of $\Delta t = 0.05\,\text{s}$.

The supporting EFB receives actual position and speed information from X-Plane, whereas target values and deviations are sent by the Simulink model. Both, the route generation as well as the airport moving map (AMM) use an experimental aerodrome mapping database (AMDB) of Jeppesen GmbH. For visualization on the EFB, a corresponding rendering engine of Jeppesen is incorporated.

The data exchange between the modules is ensured by the Octopus Datapool, which is based on UDP and TCP protocols and was developed at FSR. Additional plug-ins for Simulink and X-Plane ensure its integration.

4.2 Implementation of the Automatic Control Logic

A schematic overview of the implemented automatic control logic is depicted in Figure 4.2. Table 4.1 summarizes all relevant signals. The geometric conditions of the input values are depicted in Figure 4.3.

In contrast to the aircraft-tractor model, the speed and steering controllers are widely uncoupled. This parallel architecture ensures minimal interaction between route and speed control, allowing to switch between the different automation modes without the need for controller adjustment. The four trajectory-based automation modes can be set by applying combinations of the two switches in Figure 4.2. As the controllability of the latitudinal position error (route control) is affected by the speed control[1], this controller design can result in lasting position errors. However, the deviations observed during test runs are negligible for the purpose of this study. An upcoming iteration may include an integrated state controller optimized for a specific automation mode.

The pilot interaction is indicated by the dark gray blocks in the center of the diagram. Based on the scenario development, pilots receive route and speed information via the EFB and can apply tiller and pedals accordingly. In the designed TBDT procedures, pilot input is only desired during the automation modes with switches 1 or 2 open. Still, the connection between the manual input and aircraft brakes or tractor steering cannot be disconnected. This security mechanism allows for pilot intervention in exceptional situations regardless of the automation mode.

The following sections explain the basic characteristics of the route and speed control.

4.2.1 Route Control

The route control provides a steering angle applied by the tractor. As the proposed tractor is based on the present-day TaxiBot, an in-line steering mechanism ensures that the longitudinal axes of aircraft and tractor remain collinear at all times [IT16]. Correspondingly, the steering angle can be interpreted as the nose wheel angle of a conventionally taxiing aircraft.

[1] The requirements for controllability are summarized in Section 4.2.1 and Section 4.2.2.

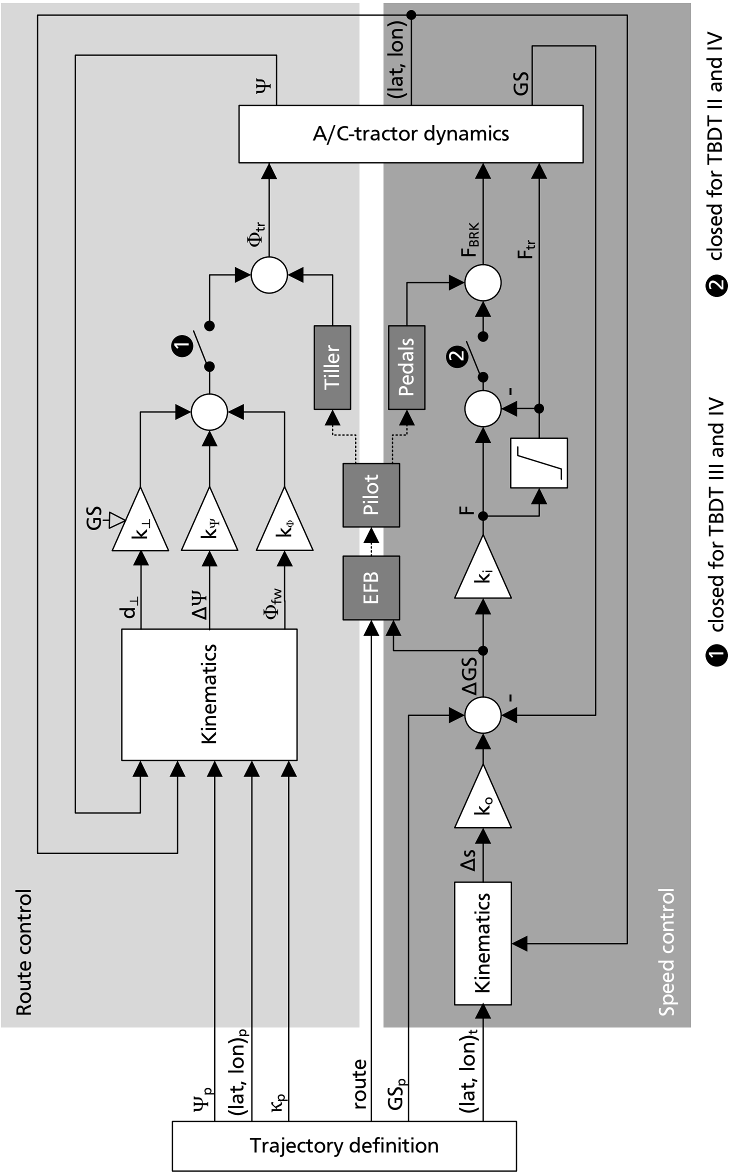


Figure 4.2.: Schematic overview of implemented automatic control architecture and pilot integration

Table 4.1.: Signals and indices visualized in Figure 4.2 and Figure 4.3

Signal	Unit	Description
d	m	distance
F	N	acceleration and deceleration force
GS	$^{m}/_{s}$	aircraft ground speed
k	–	controller gain
lat, lon	rad, rad	nose wheel position
Ψ	rad	aircraft heading
Φ	rad	steering angle
κ	$^{1}/_{m}$	trajectory curvature
ΔGS	$^{m}/_{s}$	difference between actual and target ground speed
Δs	m	position error (arc length along planned trajectory)
$\Delta\Psi$	rad	difference between actual and target aircraft heading
Index		**Description**
$_{BRK}$		applied by aircraft brakes
$_{fw}$		feed forward
$_{i}$		inner loop
$_{o}$		outer loop
$_{p}$		planned value on trajectory position closest to actual nose wheel position
$_{t}$		planned value at actual time step
$_{tr}$		applied by/via tractor
$_{\perp}$		perpendicular regarding trajectory segment closest to actual nose wheel position

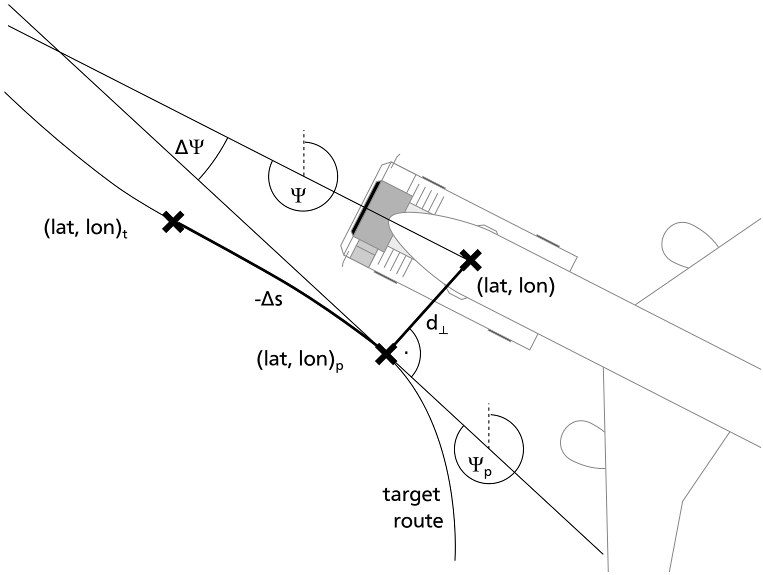


Figure 4.3.: Relevant angles and positions for controller input

In modes TBDT I and II, this steering angle is set by the pilot using the aircraft tiller. According to present-day TaxiBot operations, the tiller signal causes a nose wheel deflection which is converted into steering of the tractor wheels. In these modes, the switch 1 in Figure 4.2 remains open.

Modes TBDT III and IV involve automatic steering, meaning that switch 1 in Figure 4.2 is closed and that manual steering is only applied in emergency cases. The calculation of the steering angle for the automation is inspired by Barton who suggests a feedback and feedforward controller for car-like robots [Bar01].

The adapted implementation concerning the TBDT tractor in this study is defined by Equation 4.1 with symbols according to Table 4.1 and Figure 4.3.

$$\Phi_{tr} = d_{\perp} \cdot k_{\perp}(GS) + \Delta\Psi \cdot k_{\Psi} + \Phi_{fw} \cdot k_{\Phi} \tag{4.1}$$

An iterative approach leads to best results with the implementation of gain scheduling for $k_{\perp}$, which is defined by a linear function of the ground speed

GS. System analysis reveals stability for positive ground speeds if Equation 4.2 and Equation 4.3 are valid.[2]

$$d_{\perp} \cdot k_{\perp}(GS) + \Delta\Psi \cdot k_{\Psi} < \frac{\pi}{2} \tag{4.2}$$

$$\Delta\Psi \leq \frac{\pi}{2} \tag{4.3}$$

The independence between route and speed control causes loss of controllability when ground speed is zero. Therefore, if the final lateral position is reached, remaining position or heading deviations cannot be eliminated. Preliminary steering tests of the evaluation setup for common trajectories at Frankfurt Airport revealed perpendicular position deviations between predefined and actual nose wheel position of less than $d_{\perp,max} = 0.5\,\mathrm{m}$. As the trajectory conformance in Hypothesis 1 is limited to the longitudinal position error, the measured lateral accuracy is considered to be sufficient.

4.2.2 Speed Control

The speed control is implemented by means of a cascade structure. Depending on the arc length Δs (see Figure 4.3) along the trajectory between the target position for the current time step and the trajectory position nearest to the actual nose wheel position, the target ground speed is defined. Actual and target ground speeds are presented to the pilot on the EFB. Regardless of the automation mode, the ground speed error results in an acceleration or deceleration force. If the target force does not exceed the fatigue limit of the nose gear, the tractor applies the acceleration or deceleration on its own. If the target deceleration force exceeds the fatigue limit, additional support is required. In modes TBDT I and III, the pilot is advised by the EFB to engage the aircraft brakes in order to support the tractor and to minimize the speed deviation. In modes TBDT II and IV, the speed indicator on the EFB only provides information, while the remaining braking force is automatically applied by the aircraft brakes.

System analysis shows stability for all positive gain values ($k_o, k_i > 0$).[3] The speed is only controllable if the parallel route controller directs the aircraft-tractor combination into the required direction. Thus, the stability requirements in Equation 4.2 and Equation 4.3 are essential for controllability of the speed.

2 For the system analysis, a tricycle model of the aircraft-tractor system according to Borenstein, Everett, and Feng was used [BEF96]. Stability was investigated by analyzing the eigenvalues of the Jacobian matrix.

3 For the system analysis, the aircraft-tractor dynamic was described by a mass-damper system. Visualization of the corresponding root locus plot shows stability.

4.3 Implementation of the Human-Machine Interface

The prototypical HMI, as presented in Figure 3.21 and Figure 3.22, was developed and integrated into the simulator environment, serving as the primary support tool during TBDT.

The application running on a 10.8 inch Windows 10 tablet PC is based on the Qt 5.5 framework. The AMM widget uses the source code of the experimental software Gate-to-Gate provided by Jeppesen GmbH. Additional touch buttons allow for centering of the aircraft and for rotation of the map. The target route is sent by MATLAB Simulink to the tablet. Trajectory segments can be switched between cleared and uncleared via the instructor interface of the Simulink model. The progress indicator on the top-left automatically changes its status in conformance with the automation mode set via the instructor interface. In addition to that, individual texts can be sent by the instructor to be displayed in the communication area of the HMI. The logic of the speed indicator is explained in Section 3.5.3 and receives its input from the Simulink and the X-Plane model. The sound signal calling for supportive brake input is realized via the built in tablet PC speakers.

4.4 Underlying Scenario for Evaluation

In line with the scenario development, a taxi procedure at Frankfurt Airport serves as the basis for the simulator evaluation. The use case is a taxi-out sequence of a medium-haul narrow-body aircraft taxiing from terminal 1B on a direct route to runway 18. The trials simulate the forward taxi phase starting after push-back and terminating at the runway stop bar. Five evaluation runs cover all modes TBDT I to IV and the route-based taxi operations (RBTO) mode. During the RBTO run, conventional engine-powered taxiing is simulated and a target route without speed constraints is provided. The target trajectories for TBDT I to IV include four randomly positioned braking segments, requiring manual or automatic application of the aircraft brakes.[4] The invariant target route with an exemplary speed profile is visualized in Figure 4.4. Having completed the push-back from gate B20, the test pilots shall taxi along the taxiways N5, N and N-South to a stop bar at the northern end of runway 18. The trials focus on the pilot taxiing and the task of maneuvering the aircraft along the route or trajectory. Limiting the independent variables to *braking* and *steering*, the tasks of communication, interaction with the

[4] These braking segments are included for the purpose of evaluating the pilot's reaction to unexpected deceleration requests. Reducing the amount of speed changes is a common target for trajectory optimization algorithms (e.g. [GT12]) leading to smoother speed profiles.

pilot monitoring, engine start, coupling, and de-coupling, as well as external traffic are excluded from the trials. The visual condition during the trials is set to maximum visual range (CAVOK) at daytime.

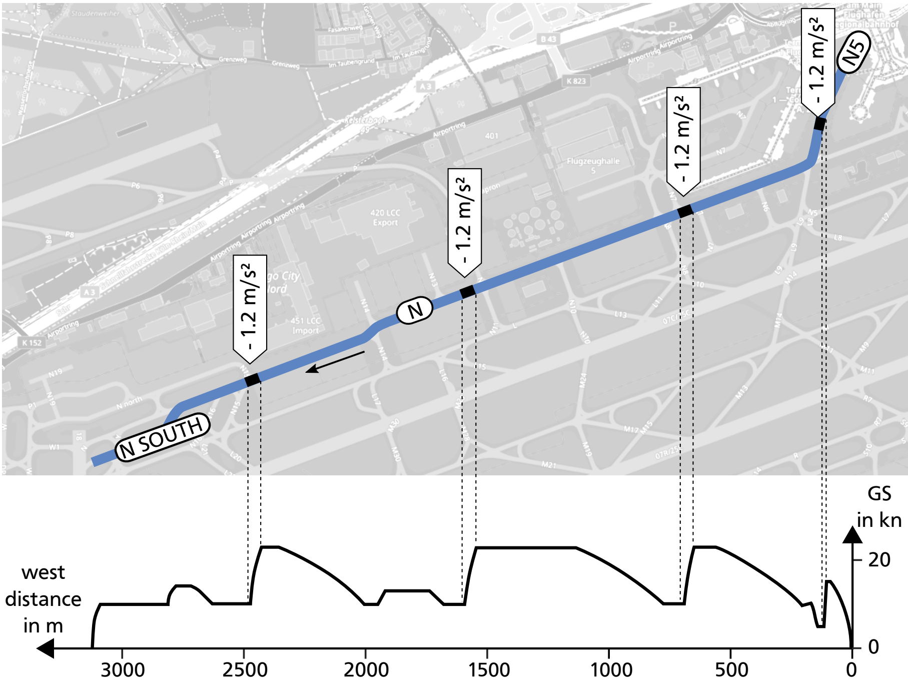


Figure 4.4.: Route and exemplary ground speed profile of trajectory for final evaluation (map data copyrighted by OpenStreetMap contributors available from https://www.openstreetmap.org)

The target speeds vary between 0 kn and 23 kn (11.8 $\frac{\mathrm{m}}{\mathrm{s}}$) with maximum deceleration rates of 1.2 $\frac{\mathrm{m}}{\mathrm{s}^2}$. This leads to a mean duration of 9.4 min per TBDT run. The distance traveled is 3690 m per run.

4.5 Description of Trials

The trials were carried out in the simulator D-AERO between May and September 2017. According to the previously described test scenario, in each trial one pilot participated as the pilot taxiing in the captain's seat. The role of the pilot monitoring was not considered in this context.

4.5.1 Participants

In total, $n = 24$ pilots of commercial airlines participated in the main simulator evaluation. All pilots were holding both an Airline Transport Pilot License (ATPL) and a commercial aircraft type rating of various narrow- and wide-body aircraft (see Figure 4.5).

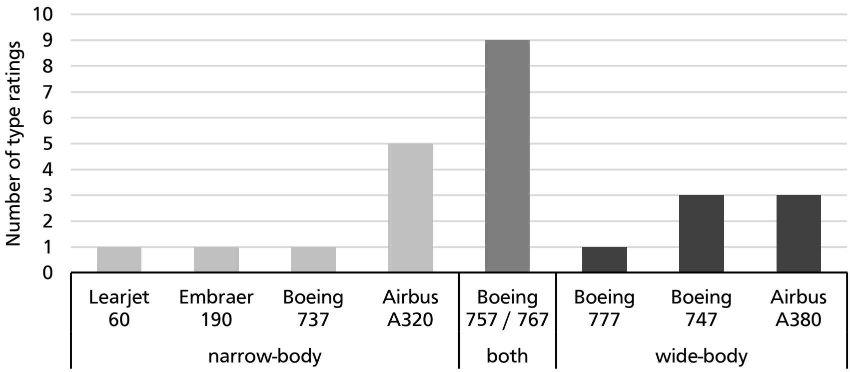


Figure 4.5.: Type ratings of participants at the time of the trials

Unlike company procedures of several airlines (see Section 1.3.2), the TBDT concept allows both the captain and the first officer to be responsible for maneuvering on ground. Consequently, the participants of the simulator evaluation were composed of captains ($n_{CPT} = 11$), first officers ($n_{FO} = 6$), and senior first officers ($n_{SFO} = 7$). All active (senior) first officers stated to have conducted a number of taxi operations while being in charge of steering and speed control before. Seven pilots claimed to be familiar with the current TaxiBot technology, while one pilot had operational experience with TaxiBot.

All participating pilots were male and had a mean age of $M = 40.2$ years ($SD = 11.1$ years, $min = 27$ years, $max = 65$ years). One of the pilots holds a type rating, but has not started the first regular flight yet (0 commercial flight hours). Another pilot has been retired for two years when participating in the trials. The mean amount of airline flight hours is $M = 8062\,\text{h}$ ($SD = 5655\,\text{h}$, $min = 0\,\text{h}$, $max = 22\,500\,\text{h}$). See Appendix F for a complete list of details regarding the participants.

The 24 pilots participated during their spare time in the trials and were not financially compensated. The recruitment process included contacting via e-mail, black board postings, and a digital posting on the intranet platform of a German airline.

4.5.2 Evaluation Procedure

Each pilot participated in a separate evaluation procedure, accompanied by one instructor (the author), with a total duration of approximately 2 h 30 min, as summarized in Figure 4.6.

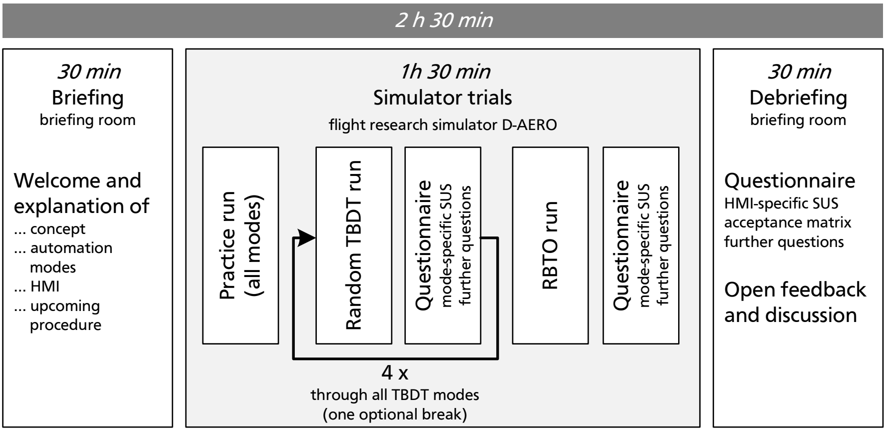


Figure 4.6.: Sequence of simulator evaluation

The briefing at the beginning of the session commenced with a presentation about the aim of the project, the general concept, the considered automation modes, the EFB application, and the upcoming simulator tasks. Uncertainties were addressed individually during or after the presentation. The following prioritization of tasks to be performed by the participants was stated:

1. Compliance with target route
2. Compliance with target speed
3. Fulfillment of additional traffic awareness task (see Figure 3.25 and Figure 4.7)

Each session started with one practice run aiming to convey a better understanding of the simulator behavior and the differences between the modes as well as to allow for practicing. During the practice run, all automation modes were presented and additional explanation was provided. Afterwards – according to the repeated measures design – each pilot participated in five evaluation runs (TBDT I to IV and RBTO). The order of the TBDT runs alternated. As 24 pilots participated, all possible sequences of the four TBDT modes were evaluated once. In every session, the RBTO procedure marked the last run. Each mode was briefly introduced by the instructor immediately before the run. Furthermore, in every evaluation run, the first segment on taxiway N5 served for the purpose of additional training, as data collection started after the first braking phase (see Figure 4.4). As explained in Section 3.6, Hypothesis 2 needs to be evaluated by means of an additional traffic awareness task. Consequently, during all runs, the pilots needed to push a hardware button on the thrust lever as soon as they were able to identify an external diamond-shaped object, shown in Figure 4.7. The color and shape of the objects consciously differ from common airport objects, vehicles, and persons, enabling a clear distinction from the airport environment. Only one object appeared at a time with a random time window between two consecutive appearances of 20 s to 30 s. The objects appeared on a fixed ground position with initial distance to the nose wheel along the planned route of 250 m and a random offset inside the range of ±30 m.

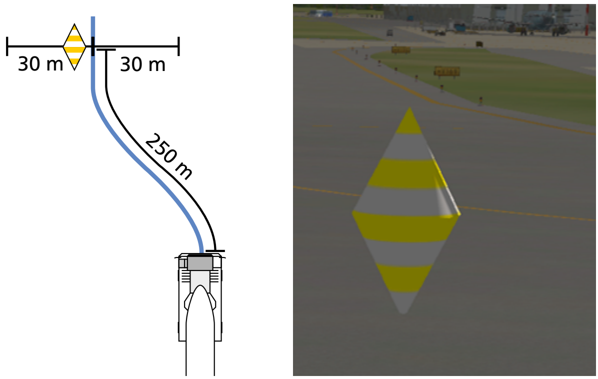


Figure 4.7.: External diamond object and relevant distances for evaluation of hypothesis 2 regarding level 1 traffic awareness

Following each run, the participants were asked to fill out pen and paper questionnaires relating to the mode-specific System Usability Scale (SUS) and further questions. There was an optional break offered to the participants after the second TBDT run.

Having completed all runs, the participants were debriefed in the briefing room. In contrast to the mode-related SUS questionnaires following each run, an additional SUS questionnaire focused on the HMI on the EFB. Moreover, the pilots were asked to complete the acceptance matrix regarding Hypothesis 4 (see Table 3.6) and to answer additional questions.[5]

Appendix G summarizes all recorded data during the trials.

[5] The results of additional questions not related to the hypotheses are presented in Appendix I.

5 Simulator Evaluation Results

The recorded data and the questionnaire results are analyzed in terms of the four main hypotheses formulated in Section 3.6. Subsequent to the presentation of relevant general findings and an analysis of the electronic flight bag (EFB) application, each hypothesis is analyzed individually by descriptive and inferential statistics. Each subsection describing the results of a measurement is directly followed by a discussion concerning the corresponding hypothesis. If beneficial, the objective and subjective measurements are substantiated by means of quotes from comments of the free-text fields in the questionnaires. The comments shall provide exemplary insight into pilots individual attitude without claiming universality. All cited comments as well as the statements of the Likert ratings are translated by the author from German. For a complete list of the original comments see Appendix J. At the end of this chapter, an overall concept assessment aims at the investigation of the global hypothesis. Descriptive plots of additional measurements, which are not analyzed in the following sections, are provided in Appendix I.

For the purpose of evaluation, all data were transfered into a MATLAB file format. The subsequent analysis and statistical tests were conducted using the statistics toolbox of MATLAB R2015a and the software IBM SPSS Statistics 24.

Most results do not meet the assumptions of a linear model. As a consequence, non-parametric tests (e.g. Friedman's analysis of variance (ANOVA) or Wilcoxon signed rank test) are applied, if appropriate. When no suitable tests exist (e.g. no robust version of the factorial repeated measures ANOVA), the data are transformed in order to meet the assumptions of normality. All test results are supplemented by the calculation of an effect size. A brief summary of the applied methodology determining the effect size is provided in Appendix H. In the following sections, the applied statistic tests are not explained in detail. For explanation of the statistical methods, refer to the textbooks of Field [Fie16] as well as of Montgomery and Runger [MR11].

In line with similar studies in this field of research, all upcoming analyses and interpretations assume a significance level of $\alpha = 0.05$.

5.1 General Findings

All of the participating 24 pilots completed the trials and evaluated all five automation modes. Consequently, 24 complete data sets are available for analysis. The pilots were aware of the varying manual tasks during the trials depending on the automation mode. One participant experienced steering difficulties during trajectory-based dispatch towing (TBDT) II. The increase of the lateral position deviation could be solved by manually reducing speed, even though the human-machine interface (HMI) did not advise him to do so.[1] Regarding the simulator environment, all participating pilots stated that the hard- and software simulated the aircraft cockpit in an appropriate way for the given trial.

5.2 Subjective Evaluation of Electronic Flight Bag Application

The developed application running on an emulated EFB forms the visual part of the HMI. The results and discussions concerning the Hypotheses 1 to 4 deal with different automation modes in general without explicitly considering the EFB application and are presented in Section 5.3 to Section 5.6. While the evaluation focuses on the effect of automation during taxiing, the EFB application serves as a "means to an end". Nevertheless, the following sections require a well-developed visual HMI for the results and conclusions to be meaningful. Otherwise, if the application receives low usability ratings and does not support the pilot in the required manner, the corresponding automation modes might be rated accordingly.

Having defined the HMI in interviews and pre-trials (see Section 3.5.2), this section provides a retrospective analysis investigating if the design adaptations fulfill their objective. Contradictory to the evaluation of the hypotheses, the participants evaluated the visual and acoustic HMI without distinguishing between different automation modes. The System Usability Scale (SUS) questionnaires regarding the EFB application were filled out at the end of all simulator runs during the debriefing.

As the resulting scores differ significantly from a normal distribution[2], a one-sample Wilcoxon signed-rank test is applied.

[1] In the briefing, it was communicated that no abnormal situations calling for a manual overwrite of an automated function without an HMI advice will occur. Accordingly, the pilot stated that he was not aware of the possibility of unplanned brake input in order to regain steering control faster.

[2] The Shapiro-Wilk test shows significant deviations from a normal distribution, $p_{SW} = 0.04$.

5.2.1 Results

As visualized in Figure 5.1, the application received a mean SUS score of $M(a_{SUS}) = 84.7$, 95 % confidence interval (CI) $[80.0, 89.3]$. According to Bangor, Kortum, and Miller [BKM09], this mean score can be interpreted as *excellent* while the expected value is significantly above *good*, $z = 3.72$, $p < 0.01$, $r_{\text{effect size}} = 0.54$.

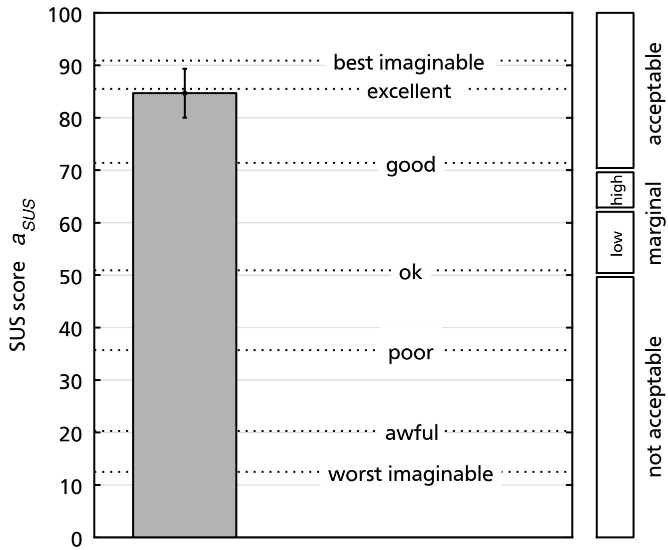


Figure 5.1.: System Usability Scale rating a_{SUS} of EFB application (mean and 95 % CI), compared with adjective ratings and acceptability scores according to Bangor, Kortum, and Miller [BKM09]

5.2.2 Discussion

The HMI was developed in line with the requirements of TBDT operations. This innovative concept has currently no counterpart of equal application in operation. Thus, the developed EFB application could not be compared to similar approaches during the main evaluation. The SUS was developed for relative comparisons of different systems in the same context [BKM09]. The adjective ratings by Bangor, Kortum, and Miller [BKM09] can be applied in order to gain an absolute classification of the user satisfaction. Nevertheless, same adjective results of systems of different contexts can result in different conclusions. Hence, adjective ratings provide an orientation, but do not allow for cross-system comparisons. Figure 5.1 compares the captured SUS score of the trials with adjective ratings and acceptability ranges, as defined by Bangor, Kortum, and Miller [BKM09]. The positive ratings (within the *acceptable* range with the mean value described by the adjective *excellent*) allow for the assumption that the subsequent tests of hypotheses are not negatively affected by the supporting EFB application. Most pilots were generally in favor of the implemented design.

> "*Visualization on EFB is very well-designed and simple.*"

> "*Very good support of EFB. Creates space for parallel tasks.*"

Suggestions for improvement were stated regarding the dynamics of the speed indicator and the provided predictability.

> "*The HMI does not support proactive taxiing.*"

> "*Speed indicator is a bit too dynamic.*"

While the effect of a less dynamic speed indicator should be analyzed in consecutive trials, the low degree of predictability is determined by the scenario design. The aim of implementing TBDT is to enable dynamic taxi trajectories, which can even change during taxiing. In this context, the provision of a trajectory prediction would lead to confusion in case of unexpected short-term adaptations of the route or speed profile.

5.3 Trajectory Error (Hypothesis 1)

Concerning the trajectory error, Hypothesis 1 implies a positive effect of automated braking (Hypothesis 1.1) and a negative effect of automated steering (Hypothesis 1.2) with all position deviations remaining below $(\Delta s)_{crit} = 22\,\mathrm{m}$ (Hypothesis 1.3).

The distributions of the measured maximum trajectory error $(\Delta s)_{max}$ defined in Section 3.6.1 show high discrepancy from a normal distribution for all relevant automation modes TBDT I to IV.[3] The non-normality of the measured position deviations of the manual braking modes TBDT I and III mainly arise out of positive

[3] The Shapiro-Wilk test shows significant deviations from a normal distribution for the considered automation modes TBDT I to IV ($p_{SW} < 0.01$).

skew and kurtosis, which could be eliminated by a logarithmic transformation. However, the trajectory errors during the automatic braking modes TBDT II and IV reveal histograms with two maxima. Furthermore, the variances of the automatic braking modes amount to less than 0.1 % of the variances of the manual braking modes.

The general difference in the distributions of the measured data can be explained by the trajectory error being a result of human performance in the manual braking modes and of the automatic control logic in the automatic braking modes. As the assumptions of normality and homoscedasticity are not met, Hypothesis 1 will be analyzed by a non-parametric Friedman's ANOVA [Fri37] followed by separate pairwise comparisons using the non-parametric Wilcoxon signed-rank test [Wil45].

5.3.1 Results

The visualization of the individual positive trajectory errors $(\Delta s)^+$ of all TBDT modes along the target route in Figure 5.2 illustrates the discrepancy in the braking behavior of the individual pilots. As expected, three areas of increased trajectory errors arise around the predefined braking positions. While Figure 5.2 provides insight into the individual progression of the trajectory errors, the following analysis focuses on the maximum trajectory errors $(\Delta s)_{max}$ of each run (see Section 3.6.1).

As expected, applying Friedman's ANOVA with the automation mode as independent variable reveals significant differences in the measured maximum trajectory error $(\Delta s)_{max}$, $\chi^2 = 25.15$, $p < 0.01$. Figure 5.3 suggests that the main effect is obviously caused by the difference between automatic and manual braking. As a consequence, the effect of the braking mode (Hypothesis 1.1) does not require further testing.

Because of this general distinction, the follow up analysis regarding Hypothesis 1.2 using two-tailed Wilcoxon signed-rank tests is conducted separately for the modes TBDT I and III as well as for TBDT II and IV. Applying the Bonferroni correction adjusts the significance level for multiple tests.[4] The results of the pairwise comparisons are summarized in Table 5.1. Significant results are printed in bold in all statistical tables included in this chapter.

Initially, the manual braking modes TBDT I and III are compared with each other. The test shows no significant effect of the steering mode on the trajectory error. There is a small to medium effect size (see Appendix H). An additional test focuses on the effect of the steering mode during automatic braking by comparing TBDT

[4] When applying multiple tests, the probability of a Type I error increases. The Bonferroni correction addresses this issue by multiplying the p-value with the number of tests (see [Fie16])

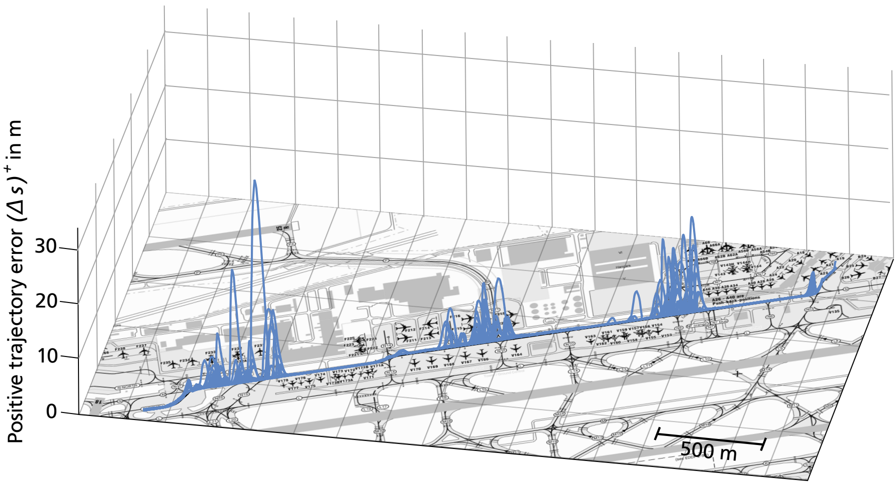


Figure 5.2.: Positive trajectory errors $(\Delta s)^+$ of all TBDT modes along taxi route (map data copyrighted by OpenStreetMap contributors available from https://www.openstreetmap.org)

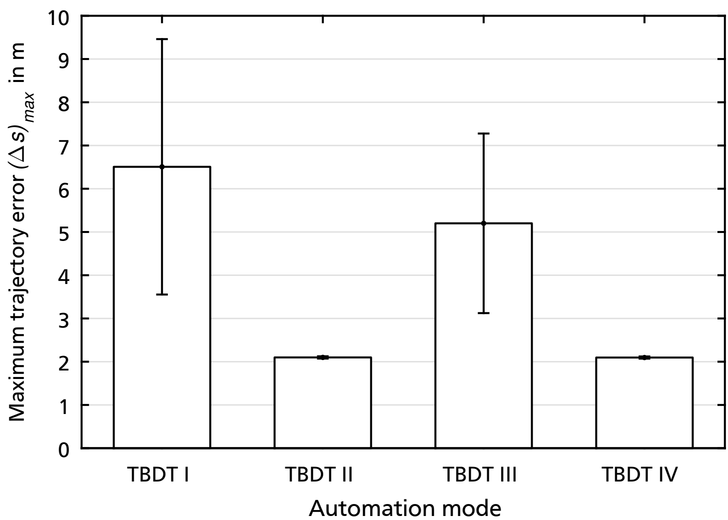


Figure 5.3.: Maximum trajectory error $(\Delta s)_{max}$ (mean and 95 % CI)

II and IV. The test statistics show no significant effect of the steering mode during automatic braking modes. The effect size can be denoted as small.

Hypothesis 1.3 is tested by conducting four one-sample one-tailed Wilcoxon signed-rank tests (see Table 5.1). Tested against the critical value of $(\Delta s)_{crit} = 22\,\mathrm{m}$, the mean trajectory errors of all TBDT modes are significantly lower. All effect sizes represent large effects.

Table 5.1.: Results of pairwise comparisons regarding the maximum trajectory errors $(\Delta s)_{max}$ using Wilcoxon signed-rank tests

Hypothesis	Automation modes compared			z	p	$r_{\text{effect size}}$
H 1.2	TBDT I	vs.	TBDT III	−1.29	0.40*	0.19
	TBDT II	vs.	TBDT IV	−0.71	0.95*	0.10
H 1.3	TBDT I	vs.	$(\Delta s)_{crit}$	**−4.11**	**< 0.01****	**0.84**
	TBDT II	vs.	$(\Delta s)_{crit}$	**−4.29**	**< 0.01****	**0.87**
	TBDT III	vs.	$(\Delta s)_{crit}$	**−4.29**	**< 0.01****	**0.87**
	TBDT IV	vs.	$(\Delta s)_{crit}$	**−4.29**	**< 0.01****	**0.87**

* two-tailed test, adjusted significance values using Bonferroni correction for multiple tests
** one-tailed test, adjusted significance values using Bonferroni correction for multiple tests

5.3.2 Discussion

Hypothesis 1 is divided into three sub hypotheses in order to gain differentiated results regarding the performance in terms of the maximum trajectory error.

The first Hypothesis 1.1, expecting a positive effect of automated braking, can be considered trivial, as the pilots had the instruction to act according to the visualized brake indicator which presents an intermediate outcome of the speed control loop. As visualized in Figure 4.2, the human input in modes TBDT I and III cannot be requested prior to the automatic braking in modes TBDT II and IV. However, the clear acceptance of Hypothesis 1.1 provides insight into the general position difference between automatic and manual braking caused by the chosen implementation.

The formulation of Hypothesis 1.2 was driven by the expectation that pilots would produce a higher trajectory error during automated steering caused by reduced arousal. However, Figure 5.3 even suggests a slight reduction of the maximum trajectory error when switching from manual steering in TBDT I to automated steering in TBDT III, while the Wilcoxon signed-rank test reveals no significant effect. These results can be further supported by the results of the Likert scale rating toward the statement "It was easy to keep the target speeds". Figure 5.4 underpins that pilots experienced no major difficulties in setting the target speed (mean value $M(a_{Likert}) = 3.8$ for both TBDT I and III) regardless of the manual braking mode TBDT I or III, $z = 0.00$, $p = 1.00$.

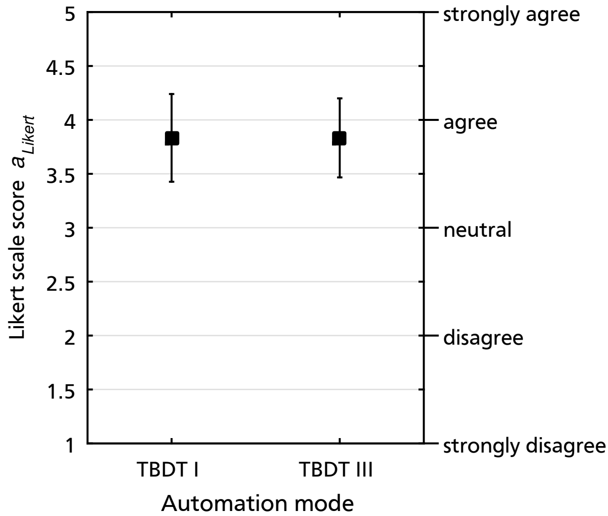


Figure 5.4.: Likert scale rating regarding statement "It was easy to keep the target speeds" (mean and 95 % CI)

As a consequence, Hypothesis 1.2 must be rejected. During discussion with the participants, several pilots stated that being responsible for manual steering causes a higher level of general attention but also increases distraction from the task of braking. It is feasible that the increased arousal and the increased distraction diminish their joint effect on performance.

In Section 3.3.1, a critical trajectory error of $(\Delta s)_{crit} = 22\,\mathrm{m}$ is defined. The test of Hypothesis 1.3 shall investigate whether even during automated braking the expected value of the position deviation is below this critical value. As all four separate comparisons show significance, Hypothesis 1.3 can be accepted. Nevertheless, these results do not preclude the fact that even though the expected value is significantly lower than the critical value, single position deviations may still exceed that value (see Figure 5.2). Figure 5.5 illustrates this circumstance by means of the corresponding boxplot[5]. One pilot produced a maximum trajectory error

[5] Outliers are defined by $(\Delta s)_{max} < p_{25} - 1.5 \cdot (p_{75} - p_{25})$ or $(\Delta s)_{max} > p_{75} + 1.5 \cdot (p_{75} - p_{25})$.

above $(\Delta s)_{crit} = 22\,\text{m}$ and five pilots exceeded $\frac{(\Delta s)_{crit}}{2} = 11\,\text{m}$. The six pilots gave two different explanations for this. Four pilots stated that they did not see the relevance of strictly following the speed advisories instead of applying smooth decelerations, which are considered to be comfortable for passengers. The other two pilots explained that they wanted to test the control mechanism in order to get a better understanding of the logic. Accordingly, the critical trajectory error was approximated or exceeded due to the conscious decision of those pilots.

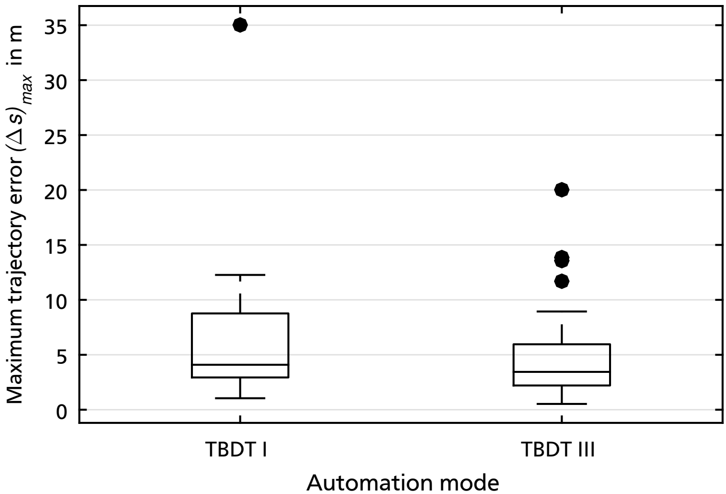


Figure 5.5.: Maximum trajectory error $(\Delta s)_{max}$ of TBDT I and III (boxplot indicating the 25^{th} and 75^{th} percentiles)

Summarizing the results regarding Hypothesis 1, the expected maximum trajectory error is significantly lower when aircraft brakes are conducted automatically but in all cases significantly below $(\Delta s)_{crit} = 22\,\text{m}$. The automation of steering has no effect on the maximum trajectory error.

5.4 Reaction Times (Hypothesis 2)

Hypothesis 2 suggests an increased level 1 traffic awareness with both automated braking (Hypothesis 2.1) and automated steering (Hypothesis 2.2). The traffic awareness during conventional route-based taxi operations (RBTO) is expected to be higher than during TBDT I and lower than during TBDT IV (Hypothesis 2.3).

Analyzing the distributions of the reaction times t_r reveals slight but significant deviations from the normal distribution for three out of five automation modes.[6] As the sample size of $n = 24$ is too small to generally refer to the central limit theorem [MR11], normal distributed data are generated by a natural logarithm transformation.[7] Consequently, the following analysis based on the transformed reaction time is calculated as

$$\widetilde{t}_r = ln(t_r). \tag{5.1}$$

As the transformation only consists of a natural logarithm, the relative order between transformed and untransformed data remains. The skew and kurtosis of the transformed data have absolute values below 2, which is acceptable according to George and Mallery [GM16].[8] Zimmerman states that homoscedasticity is not required for applying paramteric tests, if sample sizes are equal [Zim04]. Hence, when testing Hypotheses 2 to 4, potential inhomogenity of variance will not be considered.

Hypotheses 2.1 and 2.2 focus on the four trajectory-based automation modes TBDT I to IV. They are tested in terms of a two-factor repeated measures ANOVA with *braking mode* and *steering mode* as independent variables varying between the states *manual* and *automated*. As described in Section 3.6, the consideration of RBTO inhibits the application of a factorial test, as only the high-level independent variable *automation mode* (instead of the two further differentiating variables *braking mode* and *steering mode*) can be considered. Consequently, Hypothesis 2.3 is tested by Friedman's ANOVA on the untransformed data.[9]

5.4.1 Results

Figure 5.6 depicts the measured untransformed reaction times of the five tested automation modes. For comparison with the unaffected reaction times of the reference reaction study as described in Section 3.6.2 without a parallel taxi task, the corresponding results are integrated into the figure. As expected, the unaffected

6 The Shapiro-Wilk test shows significant deviations from a normal distribution for automation modes TBDT II ($p_{SW} < 0.01$), III ($p_{SW} = 0.02$), and IV ($p_{SW} < 0.01$).

7 Applying the Shapiro-Wilk test on the transformed reaction times shows no significant deviations from a normal distribution for all automation modes ($p_{SW} > 0.05$).

8 Using definition of SPSS: a value of 0 means no kurtosis.

9 The non-normality could be eliminated by a logarithmic transformation as in Equation 5.1. Nevertheless, if non-parametric robust tests exist (in this case, Friedman's ANOVA), Field advises to apply them instead of transforming the data [Fie16].

reaction times are significantly lower than the reaction times during taxiing – regardless of the mode. Applying the two-factor repeated measures ANOVA on the transformed reaction times for the automation modes TBDT I to IV reveals no significant effect of neither the braking mode (Hypothesis 2.1), nor the steering mode (Hypothesis 2.2). Furthermore, no significant interaction of steering and braking exists. The effect sizes range between small and medium. Table 5.2 summarizes the findings of the factorial repeated measures ANOVA.

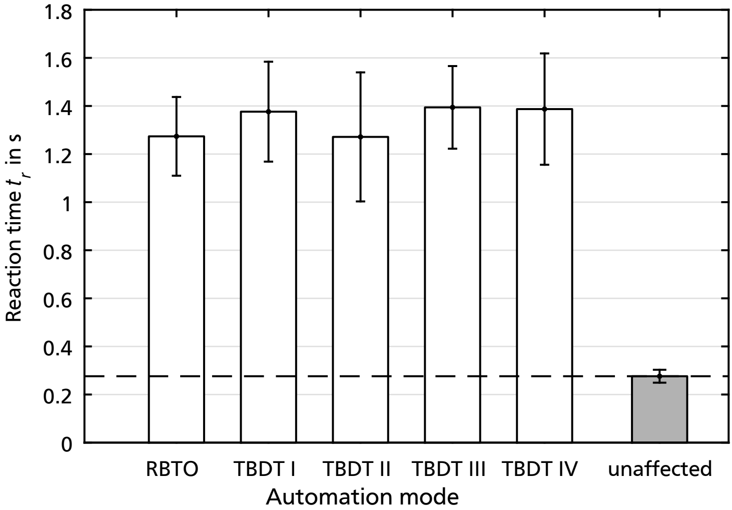


Figure 5.6.: Total reaction times t_r (mean and 95 % CI)

Table 5.2.: Results of two-factor repeated measures ANOVA: Testing the effect of steering and braking modes on the transformed reaction times $\widetilde{t}_r$

Effect	F	p	$r_{\text{effect size}}$	**Hypothesis**
Braking Mode	1.00	0.33	0.20	H 2.1
Steering Mode	1.97	0.17	0.28	H 2.2
Interaction	0.64	0.43	0.16	-

With respect to Hypothesis 2.3, the results of Friedman's ANOVA show no significant differences between the untransformed reaction times among the automation modes, $\chi^2 = 4.48$, $p = 0.34$.

5.4.2 Discussion

All Hypotheses 2.1 to 2.3 must be rejected, as no significant effect of neither the braking and steering mechanism nor the general automation mode can be observed. With regard to the concept evaluation of the TBDT modes, it can be concluded that the choice of the automation mode does not effect the mean reaction time related to level-1 traffic awareness. Furthermore, the comparison with conventional RBTO demonstrates that the shift from route- to trajectory-based operations does not result in lower level-1 traffic awareness measured in terms of the mean reaction times. Even TBDT modes with low automation support do not perform worse than the reference scenario.

Observations during the trials and the consecutive discussions with the participating pilots suggest that the expected deflection of the EFB is only an issue during the manual braking phases. Hence, the design adaptations following the pre-evaluation had a positive effect on the level-1 traffic awareness. Several pilots highlighted the usefulness of the sound signal and the color change, as it allowed them to observe the outside situation as long as no braking input is required. The following statements reflect this impression.

> "*Visualization (color change) and audio signal are very useful.*" (comment to TBDT III)

> "*Decent HMI implementation with sound and color change.*" (general comment)

Nevertheless, pilots also stated that they experienced reduced traffic awareness during manual braking phases.

> "*When it is active, the brake indicator needs a lot of attention.*" (comment to TBDT III)

This subjective perception is supported by the results of the additional Likert scale rating regarding the statement “I feel distracted by the visualization on the EFB”. Applying Friedman’s ANOVA on the ordinal data presented in Figure 5.7 reveals significant differences between the modes, $\chi^2 = 15.60$, $p < 0.01$. The post-hoc analysis summarized in Table 5.3 detects that there is a significant difference between the ratings for TBDT I and IV with medium to large effect size. Additionally, TBDT II and IV ratings seem to be generally better than those of the manual braking modes TBDT I and III (not significant).

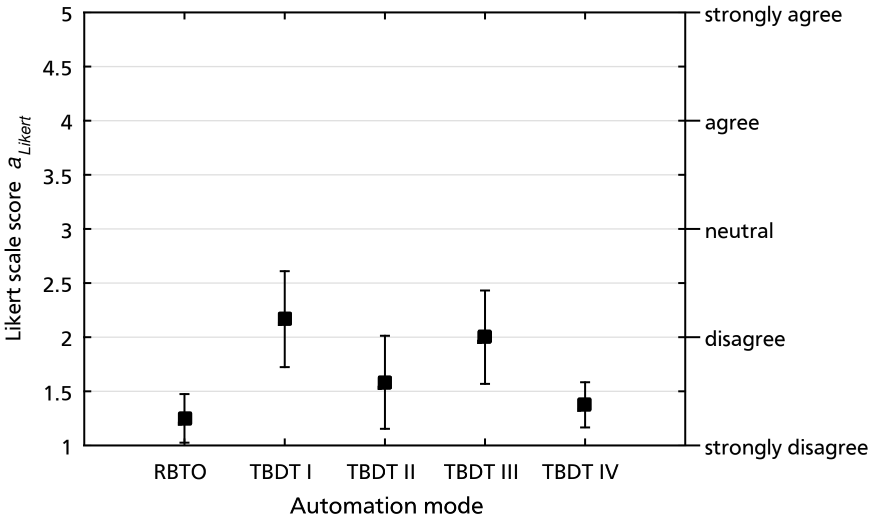


Figure 5.7.: Likert scale rating regarding statement "I feel distracted by the visualization on the EFB" (mean and 95 % CI)

Table 5.3.: Results of pairwise comparisons of Likert scale ratings regarding statement "I feel distracted by the visualization on the EFB" using Wilcoxon signed-rank test.

Automation modes compared			z	p	$r_{\text{effect size}}$
TBDT I	vs.	TBDT II	−2.23	0.16*	0.32
TBDT I	vs.	TBDT III	−0.75	1.00*	0.11
TBDT I	vs.	TBDT IV	**−3.13**	**0.01***	**0.45**
TBDT II	vs.	TBDT III	−1.65	0.59*	0.24
TBDT II	vs.	TBDT IV	−0.88	1.00*	0.13
TBDT III	vs.	TBDT IV	−2.57	0.06*	0.37

* two-tailed test, adjusted significance values using Bonferroni correction for multiple tests

The rejection of Hypothesis 2.1, which was formulated to test the distraction by means of objective data, can be explained by the relative short braking phases compared to the periods without active brake advice. As a result, the mean reaction times of the modes with manual braking are only affected insignificantly. Since reduced traffic awareness even during short manual braking phases is a safety-critical issue, the following section deals with the investigation of an additional hypothesis.

5.4.3 Additional Hypothesis 2.1b with Results and Discussion

The results of Hypotheses 2.1 to 2.3 combined with discussion and observation lead to the assumption that traffic awareness is generally not related to the automation modes. However, a negative effect of the EFB placement during manual braking phases was experienced. As a consequence, the following hypothesis is formulated:

> **Hypothesis 2.1b:** Level-1 traffic awareness decreases during manual braking phases.

The hypothesis is tested by defining two states. The state *manual braking phase* describes all time segments, in which the brake indicator on the EFB was active. This was the case during braking phases of the modes TBDT I and III. All other phases of the modes TBDT I and III as well as all phases of the remaining modes are summarized in the state *no manual braking phase*. For each participant a mean value for each phase is calculated.

The data visualized in Figure 5.8 indicate slight non-normality of the difference $\Delta t_r = t_{r,MB} - t_{r,noMB}$ between the two states.[10] Consequently, the data are tested by the Wilcoxon signed-rank test.

The test reveals that the mean reaction time significantly increases during manual braking phases with large effect size, $z = 3.66$, $p < 0.01$, $r_{\text{effect size}} = 0.53$. Hence, the additional Hypothesis 2.1b can be accepted.

The results show that the negative effect of the brake indicator on the level-1 traffic awareness is limited to the phases when it is active. Nonetheless, during these phases an increase of the mean reaction time for the perception of foreign objects of more than $\Delta t_r = 1\,\text{s}$ can be observed.

Further reduction of this remaining increase in reaction time may be reached when eliminating the need to focus on the EFB during manual braking. Approaches neglecting the use of common retrofit technologies have the potential

[10] The Shapiro-Wilk test shows significant deviations from a normal distribution for the difference Δt_r, $p_{SW} < .01$

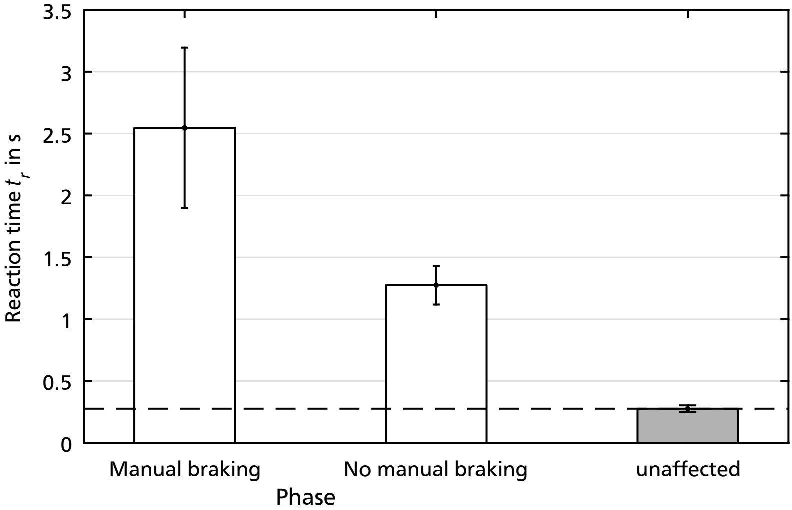


Figure 5.8.: Total reaction times t_r within and outside manual braking phases (mean and 95 % CI)

to further minimize the head-down-time. Possible implementations foresee the use of smart glasses or head-up displays. Haiduk investigates reaction times for a visual search task during general aviation flights by comparing a head-down display with smart glasses [Hai17]. A former study by Srinivasan and Jovanis compares reaction times to external events between head-down and head-up displays in a car driving task [SJ97]. As both studies reveal no significant differences in reaction times, no general interrelation can be stated. Nevertheless, a consecutive study for the specific task of following speed guidance during taxiing comparing the developed EFB application with corresponding applications on a head-up display or on smart glasses may lead to different results. One participating pilot of the main evaluation further advises to integrate the speed indicator into the existing primary flight display (PFD). The integration would place the important speed information in a location which may be easier to combine with monitoring the outside situation. While this suggestion matches the opinion of some pilots during the expert interviews (see Section 3.5.1), it is not compatible with the retrofit approach of the concept in this study.

5.5 System Usability Scale Ratings (Hypothesis 3)

Hypothesis 3 suggests increased user satisfaction with both automated braking (Hypothesis 3.1) and automated steering (Hypothesis 3.2). The user satisfaction concerning conventional RBTO is expected to be higher than concerning all TBDT modes (Hypothesis 3.3).

The results of the SUS questionnaire a_{SUS} show small deviations from the normal distribution.[11] Analogous to the approach in Section 5.4, the data are transformed for testing. As the raw data are negatively skewed for all automation modes, a reverse score transformation is applied. In an iterative process, best results were achieved with the square root transformation

$$\widetilde{a}_{SUS} = \sqrt{a_{SUS,max} - a_{SUS}} = \sqrt{100 - a_{SUS}}. \tag{5.2}$$

The transformed scores exhibit no significant deviations from the normal distribution.[12] For further analysis of the transformed data, it needs to be considered that the transformation reverses its order. According to George and Mallery, the absolute values for skew and kurtosis for the transformed as well as for the untransformed data are of an acceptable amount below 2 [GM16].

The Hypotheses 3.1 and 3.2 are tested by a two-factor repeated measures ANOVA with the two independent variables *braking* and *steering*. Hypothesis 3.3 additionally considers the mode RBTO, which does not allow for differentiation between steering and braking. Consequently, Hypothesis 3.3 is tested in terms of a non-parametric Friedman's ANOVA.

5.5.1 Results

The measured untransformed SUS scores a_{SUS} are presented in Figure 5.9. The impression of small deviations compared to the standard errors can been confirmed by a two-factor repeated measures ANOVA. Neither the steering mode nor the braking mode nor their interaction significantly affect the mean transformed SUS scores of the modes TBDT I to IV. The corresponding statistics are summarized in Table 5.4.

The application of Friedman's ANOVA allows for the consideration of RBTO with *automation mode* as independent variable. The results regarding Hypothesis 3.3

[11] The Shapiro-Wilk test shows significant deviations from a normal distribution for automation modes TBDT II ($p_{SW} < 0.01$) and IV ($p_{SW} = 0.04$) as well as for mode RBTO ($p_{SW} < 0.01$).

[12] Applying the Shapiro-Wilk test on the transformed SUS scores shows no significant deviations from a normal distribution for all automation modes ($p_{SW} > 0.05$).

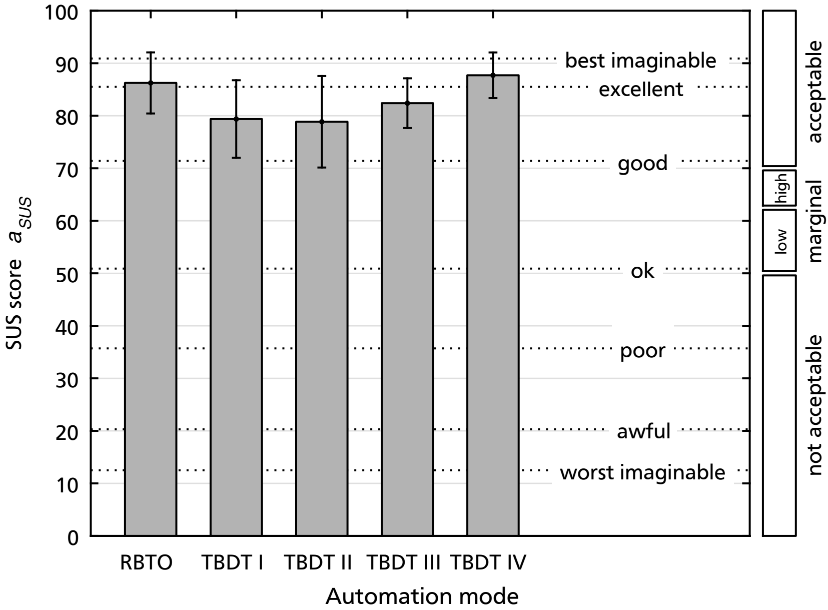


Figure 5.9.: System Usability Scale Rating a_{SUS} of automation modes (mean and 95 % CI) compared to adjective ratings and acceptability scores according to Bangor, Kortum, and Miller [BKM09]

Table 5.4.: Results of two-factor repeated measures ANOVA for testing the effect of steering and braking modes on the transformed SUS score $\tilde{a}_{SUS}$

Effect	F	p	$r_{\text{effect size}}$	**Hypothesis**
Braking Mode	2.13	0.16	0.29	H 3.1
Steering Mode	2.01	0.17	0.28	H 3.2
Interaction	1.88	0.18	0.27	-

show that there is no significant effect of the automation mode regarding captured SUS scores, $\chi^2 = 6.53$, $p = 0.16$.

5.5.2 Discussion

The Hypotheses 3.1 to 3.3 address the effect of the braking mode, the steering mode, or the general automation mode on the user satisfaction of the pilots. A qualitative analysis of the results as demonstrated in Figure 5.9 implies that a slight effect exists with best ratings for the fully automated mode TBDT IV and the conventional mode RBTO. Yet, these effects are not significant. Therefore, when considering the SUS scores, the results reveal that no trajectory-based automation mode is rated significantly lower than the present-day taxi operations. While the main motivation for introducing TBDT is the reduction of emission and taxi times, the user satisfaction of the pilots shall not be reduced either. Conversely, increased SUS scores are not mandatory for the overall assessment of the concept. According to the results, the evaluated system allows for the implementation of surface trajectory-based operations (STBO) without reducing subjective system usability.

While no significant results regarding the optimal TBDT mode exist, the observed trend in Figure 5.9 was supported by discussion and open comments of the participants. Several pilots stated that they are not in favor of mixed automation modes. The following statements illustrate the preference toward clear modes, with either full automation (TBDT IV) or minimal automation (RBTO).

> "*Compared to the low automation [in TBDT I], no automation would be better.*" (comment to TBDT I)

> "*Awkward allocation of automated functions. Difficult to steer, if speed is not controllable.*" (comment to TBDT II)

> "*I prefer to either hand over to all functions to automation or no function at all.*" (general comment)

Taking into account the measured data as well as the qualitative feedback, Hypotheses 3.1 and 3.2 must be rejected. Nonetheless, indications that the implementation of TBDT shall be accompanied by further automation are given. The ranking of RBTO between TBDT I and TBDT IV of Hypothesis 3.3 also needs to be rejected and cannot be supported by qualitative feedback either. Instead, the pilots seem to prefer RBTO or TBDT IV without any clear determination.

Although no significant differences between the modes could be identified, all modes received high absolute subjective usability ratings. Applying the proposed scale of Bangor, Kortum, and Miller, the adjective ratings range between *good* and *excellent*.[13] Figure 5.9 visualizes this categorization and further points out that all ratings can be considered to be in the *acceptable* range.

5.6 Acceptance Ratings (Hypothesis 4)

Hypothesis 4 suggests that pilots are willing to hand over manual tasks to automation when safety, ecological efficiency, or time efficiency benefits are expected.

The results of the acceptance matrix in Table 3.6 comprise 10 combinations.[14] Except the distribution of the safety perception of automated steering, all distributions have significant deviations from the normal distribution.[15] For this reason, all analyses are carried out with non-parametric tests.

To gain a first impression, the initial part of the analysis deals with pairwise comparisons between the automation of steering and of speed changes for each TBDT goal and for the willingness of the pilots to hand over that function. These analyses are conducted by means of Wilcoxon signed-rank tests. Subsequently, Hypothesis 4 is tested by means of a correlation analysis. As most data are not normal distributed, the non-parametric Spearman's correlation is applied.

5.6.1 Results

The mean values and the 95 % CI of the results of the Likert matrix (see Table 3.6) are depicted in Figure 5.10.

The pairwise comparisons in Table 5.5 show that the expected safety benefit does not significantly differ between the automation of steering or of speed changes. On the contrary, the ecological efficiency, the taxi time, and the predictability receive significant higher subjective ratings for automated speed changes with large effect sizes. The willingness of the pilots to hand over a function to automation has Likert scale ratings slightly above $a_{Likert} = 3$ with no significant effect of the automated function.

[13] See Section 5.2.2 for general considerations concerning the comparability of adjective SUS ratings.

[14] (Automated Steering + Automated Speed Control)$\cdot$ (4 TBDT goals + willingness to hand over) $= 10$ combinations

[15] The Shapiro-Wilk test shows significant deviations from a normal distribution for all categories ($p_{SW} < 0.05$) except for the safety perception of automated steering ($p_{SW} = 0.05$).

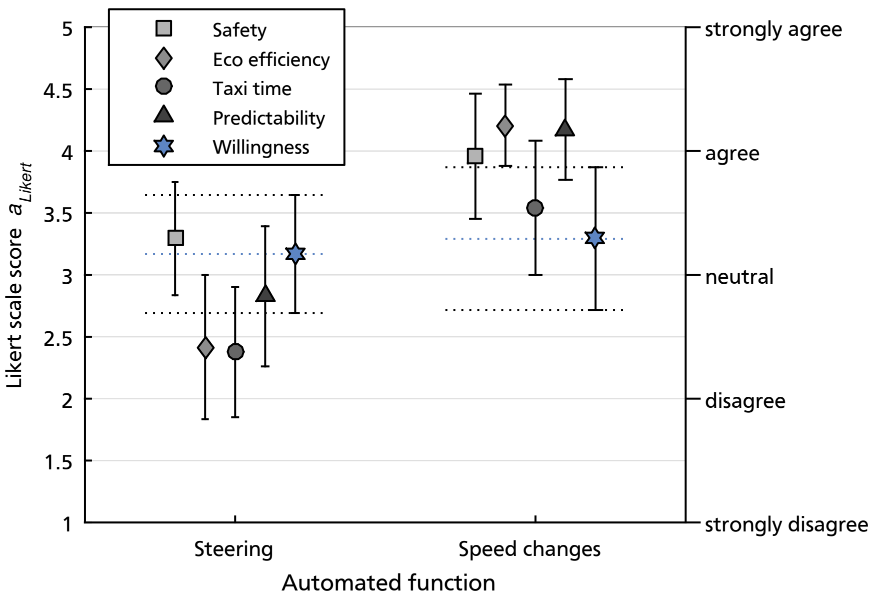


Figure 5.10.: Estimation of pilots whether automation of steering or speed changes improve safety, ecological efficiency, taxi time, and predictability versus willingness to hand over these functions to automation (mean and 95 % CI)

Table 5.5.: Results of pairwise comparisons for expected benefits of automated steering and those of automated speed changes using Wilcoxon signed-rank test

TBDT goal	z	p	$r_{\text{effect size}}$
Safety	2.36	0.10*	0.34
Ecological efficiency	**3.89**	**< 0.01***	**0.56**
Taxi Time	**3.69**	**< 0.01***	**0.53**
Predictability	**3.55**	**< 0.01***	**0.51**
Willingness	0.69	1.00*	0.10

* two-tailed test, adjusted significance values using Bonferroni correction for multiple tests

Following the identification of significant differences, Hypothesis 4 is tested by investigating the correlation between the willingness to hand over a manual task to automation and the expectation of the pilots with respect to the specified TBDT goals (*safety*, *ecological efficiency*, *taxi time* and *predictability*). Table 5.6 summarizes the correlation analysis by presenting the Spearman's correlation coefficient r_S and the probability $p(r_S = 0)$ for each combination of willingness and the TBDT goals separated by automated steering and speed changes.

Table 5.6.: Results of the Spearman's correlation r_S between willingness to hand over a function to automation and the expected benefit on safety, ecological efficiency, taxi time and predictability.

Relationship between willingness to hand over and expected...	**Steering**	**Speed changes**
... safety benefit	$r_S = 0.30$ $p = 0.08^*$	$\boldsymbol{r_S = 0.55}$ $\boldsymbol{p < 0.01}^*$
... ecological efficiency benefit	$r_S = -0.24$ $p = 0.13^*$	$r_S = 0.25$ $p = 0.12^*$
... taxi time benefit	$r_S = 0.17$ $p = 0.22^*$	$r_S = 0.17$ $p = 0.21^*$
... predictability benefit	$r_S = 0.01$ $p = 0.48^*$	$\boldsymbol{r_S = 0.38}$ $\boldsymbol{p = 0.03}^*$

* one-tailed test, testing the hypothesis of $r_S = 0$

The willingness to hand over speed changes significantly correlates with expected safety benefit as well as with expected predictability benefit.

5.6.2 Discussion

Figure 5.10 and Table 5.5 reveal that the expected benefits regarding the TBDT goals are higher for automated speed changes than for automated steering. Especially benefits regarding ecological efficiency, taxi time, and predictability for automated steering are significantly lower than those for automated speed changes. Although the mean ratings for automated speed changes are generally higher, the willingness of the pilots to hand over speed changes is not significantly higher than to hand over steering. As the mean values and CIs do not provide insight into the individual correlation between the expectations of the pilots and their willingness to hand over functions, Hypothesis 4 is analyzed by means of a correlation analysis.

Hypothesis 4 suggests a positive correlation between expected benefits and the willingness to hand over functions to automation. With regard to steering, no significant effects can be observed. Nonetheless, the highest correlation with willingness to hand over automated steering is measured for the expected safety benefit. As there is a 8 % chance that the true correlation is negative, the effect is likely but not significant (see $p = 0.08$ for expected safety benefit for handing over steering in Table 5.6). With respect to automated speed changes, the willingness to hand over these functions correlates significantly with the expected safety benefit and the expected predictability benefit. It is worth emphasizing that the highest correlation with a high significance value is reached for the relationship between expected safety benefit and willingness to automate speed changes with a large correlation coefficient of $r_S = 0.55$.

Summarizing these results, Hypothesis 4 can be partly accepted since there exists an interrelationship between the willingness of the pilots to hand over functions to automation and the expected benefit. Yet, these effects were not observed for the automation of steering and are limited to the two TBDT goals *safety* and *predictability*.

During open feedback and discussion, a general consciousness that automation can support the TBDT goals as well as the willingness of pilots to hand over tasks became apparent. Nevertheless, several participants claimed to still prefer the manual taxi process. They stated the importance of being in-the-loop as the main reason. As further reasons they state that manual taxiing would be more fun and that they would need to be in charge due to their responsibility for the passengers. The following exemplary statements relating to the manual taxi mode RBTO underpin this finding:

> "*In RBTO you keep the feeling to be pilot in command.*" (comment to RBTO)
>
> "*Much more fun.*" (comment to RBTO)
>
> "*[Pilots keep] maximum control of all systems.*" (comment to RBTO)

5.7 Concept Assessment

With regard to the TBDT concept, the evaluation revealed that the logics and task distributions of all considered automation modes are comprehensible. The only misunderstanding mentioned in Section 5.1 (loss of steering control due to wrong interpretation of allowed simulator input) refers to the simulation scenario and not to the concept itself.

The test results, evaluating performance, traffic awareness, user satisfaction, and acceptance are summarized in Table 5.7.

Table 5.7.: Summary of tested hypotheses

Nr.	Test	Conclusion
1.1	✓	Implemented speed control functions properly
1.2	✗	No significant effect of steering on trajectory error
1.3	✓	No excess of critical trajectory error for all automation modes
2.1	✗	No significant effect of automation mode on mean traffic awareness measured by mean reaction time
2.2	✗	
2.3	✗	
2.1b	✓	Significant reduction of traffic awareness during manual brake phases
3.1	✗	No significant effect of automation mode on user satisfaction
3.2	✗	
3.3	✗	
4.1	✓/ ✗	Acceptance for automated speed changes when safety or predictability benefits expected

The tests of Hypotheses 1.1 to 1.3 reveal that all automation modes allow for a sufficient trajectory conformance. The results account for the implementation of STBO by means of an external towing vehicle, enabling the pilot to follow full 4D trajectories – regardless of the automation mode.

Besides ensuring high trajectory conformance, the concept needs to maintain a sufficient degree of traffic awareness. The results reveal that the mean reaction time for capturing external objects does not increase significantly with the introduction of TBDT (Hypotheses 2.1 to 2.3). On the contrary, when adjusting the measurement, manual brake phases cause time-limited phases with significantly lower traffic awareness (Hypothesis 2.1b). Even limited periods of increased reaction times are not acceptable for introducing novel operations, as safety must at least remain at the same level. As a consequence, the elimination of manual brake phases is recommended. Keeping the general TBDT concept unchanged, two possible approaches are conceivable. One option is the modification of aircraft enabling automated braking – as envisaged in TBDT II and IV – meaning a reliable but complex and costly solution. In an alternative approach, the safety of the retrofitable modes TBDT I and III can be increased by adjusting the trajectory characteristics. In case of decelerations not exceeding the limits of the tractor or nose wheel, additional brake support or modification of the avionics are not required. The developed EFB speed indicator can be maintained, but needs to be activated in emergency situations calling for spontaneous braking only. Real time and fast time simulations have to evaluate the approach of adjusted trajectory planning. Those results provide insight into the operational performance with limited deceleration capabilities and into the probability of unplanned emergency brake instructions.

In accordance with the user-centered design approach, objective measurements need to be supplemented with subjective ratings of the system users. A possible implementation of the innovative TBDT procedures would be supported by pilots who express a high degree of user satisfaction. Consequently, the insignificant results of hypotheses 3.1 to 3.3 support the concept of TBDT, as the good SUS ratings of conventional procedures can also be achieved with the novel concept.

The initial motivation for STBO and hence for TBDT is based on benefits regarding safety, ecological efficiency, and time efficiency (see Section 1.4). The real time simulator evaluation of this study reveals that pilots also anticipate these benefits when speed control is transfered to automation. The partially acceptance of Hypothesis 4 shows that automated acceleration and deceleration is supported by those pilots who expect corresponding safety and predictability enhancements. On the contrary, when implementing TBDT, hypothetical complications with negative impact on safety or predictability might result in low pilot acceptance.

Summing up the results, the trajectory execution concept can be confirmed by the simulator evaluation, while alterations to the trajectory definition are suggested. With regard to the global hypothesis, the evaluation demonstrated the applicability of TBDT predicting acceptable performance, traffic awareness, user satisfaction, and acceptance.

6 Conclusion and Outlook

Surface trajectory-based operations (STBO) have the potential to enhance predictability of the ground movement of aircraft by simultaneously reducing taxi times and emissions. This dissertation introduces a novel concept for future surface operations, facing the pending challenge of enabling present-day aircraft to follow trajectories on ground. By means of a broad inclusion of stakeholders, this concept – referred to as trajectory-based dispatch towing (TBDT) – was specified and adjusted. The subsequent iterative process aimed at the integration of pilots into TBDT. A user-centered design approach included pilot and expert interviews as well as an initial simulator campaign evaluating different human-machine interface (HMI) concepts. The final simulator trial with 24 commercial airline pilots investigated and evaluated the following three aspects in regards to TBDT:

- The feasibility of the operational concept from the perspective of pilots should be confirmed.
- The developed and pre-evaluated electronic flight bag (EFB) HMI should be assessed with respect to user satisfaction and its ability to support the pilot during all defined automation modes.
- The detailed differentiation between potentially automated steering and braking and their combinations (TBDT I to IV) as well as the comparison with conventional operations (route-based taxi operations (RBTO)) should provide insight into the preferred amount of automation. The assessed measures were *performance*, *traffic awareness*, *user satisfaction*, and *acceptance*.

The evaluation results revealed that all automation modes have the potential to successfully support pilots during TBDT. The developed graphical and acoustical interface on the EFB provides straightforward assistance during the whole taxi process and demonstrated high user satisfaction. Moreover, the differentiation between the TBDT modes I to IV and RBTO draws the following main conclusions:

- Full 4D STBO can be realized by all TBDT modes. Even during manual braking phases, the trajectory error is not safety critical.
- The effect of head-down HMIs on traffic awareness on ground needs particular attention as the required time for the perception of external objects increases significantly during manual brake phases.

- The automation mode has no significant effect on the user satisfaction of the pilots. Nevertheless, qualitative results suggest a clear distinction between manual and automated functions.

- The willingness of pilots to transfer manual functions to automation is generally higher when the expected benefits regarding safety and predictability are conveyed successfully.

Several recommendations as well as future research concerning operational considerations, surface trajectory generation, and corresponding HMI development are presented in the following concluding sections.

6.1 Recommendations

The following recommendations are deduced from the main simulator evaluation as well as from the preceding design and development process. In line with the investigation of this dissertation, the recommendations focus on optimum pilot integration. The recommendations are clustered into the application areas *operational concept*, *trajectory generation*, and *cockpit HMI*.

Operational concept

- Potential traffic mixes are a critical aspect when integrating surface trajectories step by step. The results of the evaluation reveal that current efforts regarding future aircraft generations should be continued, as heterogeneous traffic mixes on ground can be attenuated with the implementation of TBDT for conventional aircraft.

- When implementing precise surface trajectories, pilots need assistance with speed control, which is included in all investigated TBDT concepts. Previous studies with full manual speed control are feasible but require significantly higher tolerances and may be not applicable for full 4D STBO.

- Manual support during brake phases is conceivable, but requires additional attention of the pilots, which causes a decrease of traffic awareness. This may be counteracted by a revised task allocation between captain and first officer.

- From a pilot's perspective, steering does not need to be automated. Automated steering has no positive or negative effect on performance, traffic awareness, or subjective satisfaction. Nevertheless, in case of single-pilot operations or additional task allocation to the cockpit crew, automated steering could distribute mental resources more effectively.

- Although, no significant interaction effects between automated and manual tasks were observed, discussion showed that the pilots prefer a clear distinction between automated and manual tasks. This should be considered when implementing partly automated taxi procedures.
- As long as the pilot is responsible for ensuring safe taxi operations, every tiller or pedal input shall override the automatic steering and speed control.
- When applying or enhancing TBDT, as well as other STBO concepts, a holistic approach should include all involved stakeholders. The feedback gained during this study confirmed that great acceptance can be reached by including users in the development process.

Trajectory generation

- Full 4D trajectories with continuous speed profiles (as visualized in Figure 3.10) are feasible and can be executed by means of all TBDT modes.
- Planned trajectories need to be supplemented with segment-specific maximum speed definitions in order to allow for automatic reduction of position deviations after manual pilot interaction.
- When implementing a TBDT mode with manual braking, planned trajectories should be executable without additional braking support of pilots. Ensuring this aspect, head-down times, which reduce traffic awareness, can be minimized.
- Safety margins for trajectory generation can be kept low and should be based on current specifications defined by the International Civil Aviation Organization (ICAO) (see [Int04, pp. 3-10,4-2,4-3]). The evaluation revealed mode-specific mean trajectory errors below 7 m, with expected values being significantly below the calculated critical value of 22 m.

Cockpit HMI

- The investigated HMI is applicable for supporting the trajectory execution of both TBDT or other STBO concepts.
- On the ground, the number of guidance functions on the EFB should be minimized.
- When time critical guidance is provided via an EFB, a short acoustic signal should catch the attention of the pilot.

- TBDT-specific functions should be incorporated into existing EFB applications.
- For speed guidance, qualitative comparisons of actual and target speeds provide an appropriate relation between simplicity and informativeness.
- When introducing new operational concepts like TBDT, pilots are in favor of a visual progress indicator.

6.2 Future Research

ICAO as well as regional agencies, the Federal Aviation Administration (FAA) and European Aviation Safety Agency (EASA), propose trajectory-based surface operations and their successive implementation [Nex11; SES15; Int16d]. Several research activities showed promising efficiency benefits [Oku+16; HCF14; Swe+07]. As a consequence, ongoing research investigates methods for introducing surface trajectories into daily airport operations. The implementation road maps (e.g. [Int16d; Foy+11]) propose a gradual shift without specifying fixed target dates. Due to the expected successive implementation, the traffic mix of differently equipped aircraft will be one of the major challenges. The TBDT approach addresses this issue by enabling an increase in the amount of trajectory-capable aircraft without extensive modifications. Subsequently, further research efforts should focus on the TBDT concept and complement the user-centered investigation carried out in this dissertation.

In terms of the **operational concept**, especially TBDT modes with high automation enable the reallocation of tasks within the cockpit crew. Accordingly, further studies should investigate the cooperation of captain and first officer in the cockpit, while simultaneously evaluating their availability for additional tasks.

With regard to **trajectory generation**, the results of this dissertation define the boundary conditions for TBDT-suited trajectories. The proposed trajectories were evaluated from the perspective of pilots. Further research needs to include these insights into fast-time simulations, evaluating the eligibility of TBDT concerning complete airport traffic mixes. In particular, infrastructure considerations in terms of parking and maneuvering of de-coupled tractors should be evaluated. This will provide findings concerning the relation between possible future traffic mixes and surface trajectory performance.

The developed **cockpit HMI** should be compared experimentally to other available visualization technologies, such as head-up displays, off-board visualizations, or modifications of the primary cockpit displays, in a simulator environment. For this purpose, existing approaches, presented in Section 2.1, could be adapted to the use case of TBDT. With respect to the investigated EFB HMI, different opinions concerning the dynamics of the speed indicator were collected. Further development should concentrate on the dependency between speed indicator dynamics, trajectory conformance, and user satisfaction. The prototype system evaluated in this thesis can be classified into Technology Readiness Level 4 (validated in Laboratory). Correspondingly, upcoming evaluations need to include more variables into the simulator environment with subsequent operational tests in the realspace environment of an airport. These on-site evaluations require the current TaxiBot technology to be enhanced to allow for dynamically changing, rather than static, position-specific target speeds.

In conclusion, TBDT operations offer a wide range of consecutive research activities. The results as well as the developed methodology of this dissertation provide a promising basis for successive, versatile investigations contributing to future safe and efficient surface operations.

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A Airport Collaborative Decision Making Timeline

Table A.1.: Abbreviations for time steps and messages in Figure A.1 and Figure A.2

AEBT	actual end boarding time
ALUT	actual line-up time
ARDT	actual ready time
ASBT	actual start boarding time
CTOT	calculated take-off time
EIBT	estimated in-block time
ELDT	estimated landing time
EOBT	estimated off-block time
EXIT	estimated taxi-in time
EXOT	estimated taxi-out time
MTTT	minimum turnaround time
TOBT	target off-block time
TSAT	target start-up approval time
TTOT	target take-off time
DPI	departure planning information
FUM	flight update message

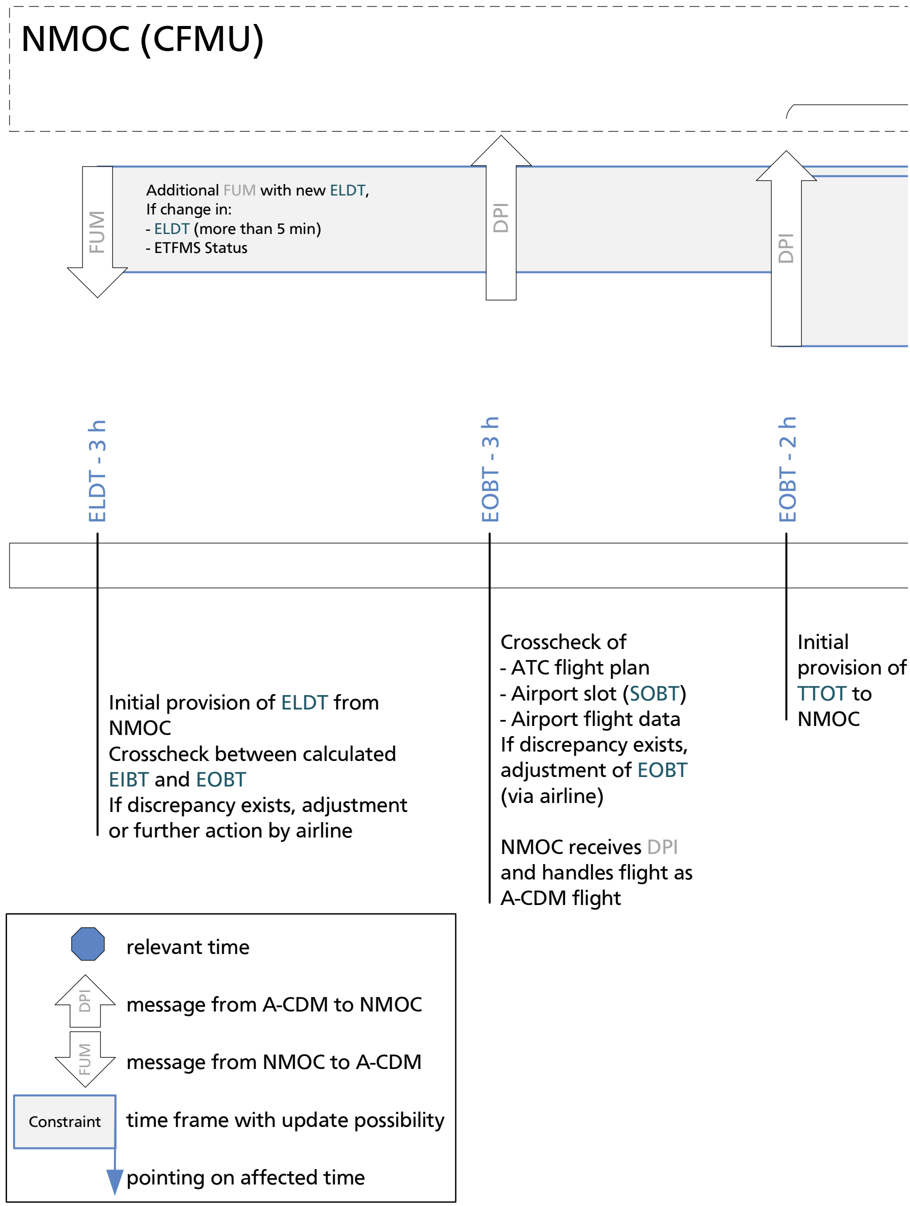

Figure A.1.: A-CDM timeline (illustrated by author on the basis of [Air12]) (1/2)

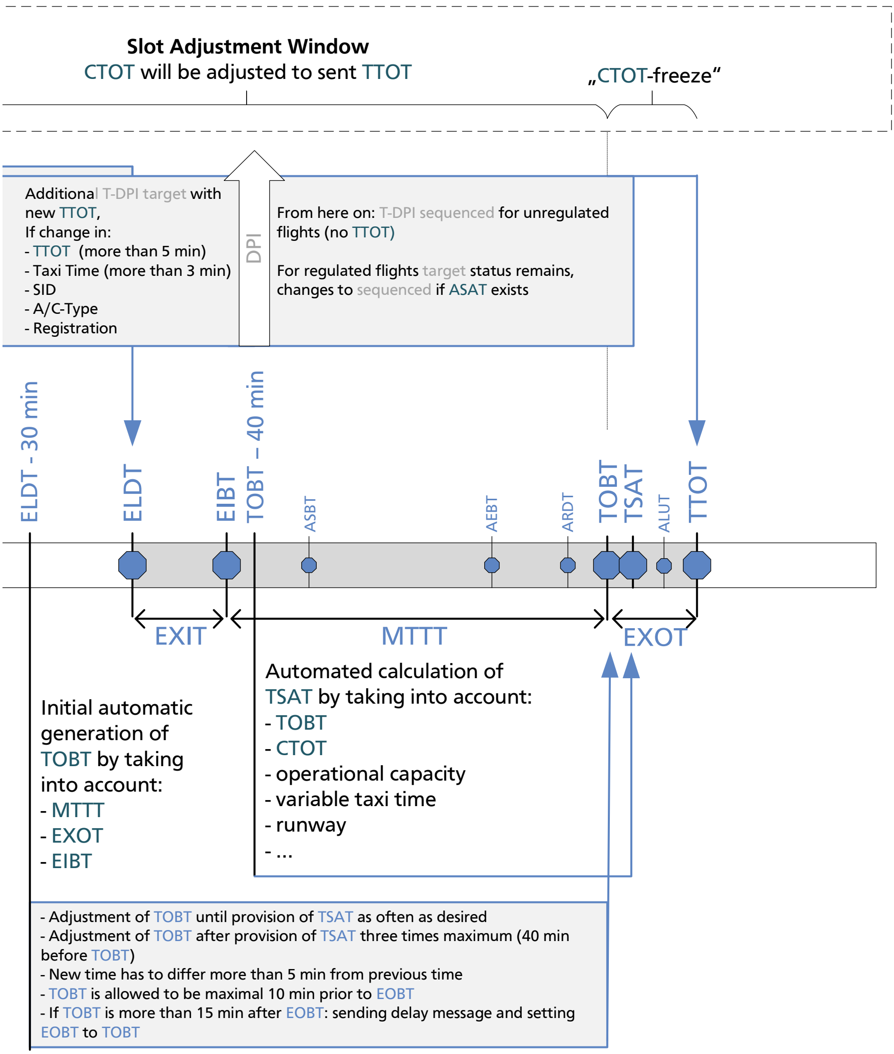

Figure A.2.: A-CDM timeline (illustrated by author on the basis of [Air12]) (2/2)

B Defining the Critical Position Error

The International Civil Aviation Organization (ICAO) defines a minimum longitudinal distance between two aircraft of $s_t = 200\,\mathrm{m}$ [Int04, p. 4-3]. If the preceding aircraft of maximum length brakes unplanned with its maximum deceleration, the situation depicted in Figure B.1 occurs.

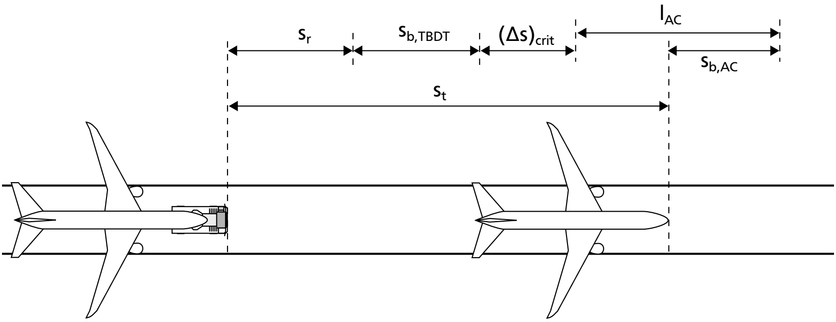

Figure B.1.: Graphical derivation of critical position error $(\Delta s)_{crit}$ (illustrated by author incorporating reference distances of [Int04, pp. 3-10,3-11,4-2,4-3])

Based on the values summarized in Table B.1, a distance of $(\Delta s)_{crit} = 22\,\mathrm{m}$ remains which equals the maximum allowable position error of the aircraft-tractor combination compared to the target position.

$$(\Delta s)_{crit} = s_t - (t_r \cdot v_b + \frac{v_b^2}{2a_b}) + \frac{v_a^2}{2a_a} - l_{max} = 22\,\mathrm{m} \tag{B.1}$$

Table B.1.: Description of values considered for determination of critical position deviation

Symbol	Value	Description	Source
s_t	200 m	minimum longitudinal spacing	[Int04]
t_r	5 m	total reaction time (pilot, controller, system, margin)	[Int04]
v_b	13.89 $\frac{m}{s}$	maximum speed of tractor-aircraft combination	TaxiBot performance
v_a	13.89 $\frac{m}{s}$	speed of preceding aircraft	analogue to v_b
l_{max}	76 m	maximum length of proceeding aircraft	length of Boeing 747-8
a_a	2 $\frac{m}{s^2}$	maximum deceleration of proceeding aircraft	[Int04]
a_b	1.2 $\frac{m}{s^2}$	maximum deceleration of target trajectory	trajectory definition *

* Based on considerations regarding passenger convenience as explained in Section 4.4

C Swim-Lane Diagram of TBDT-In Process

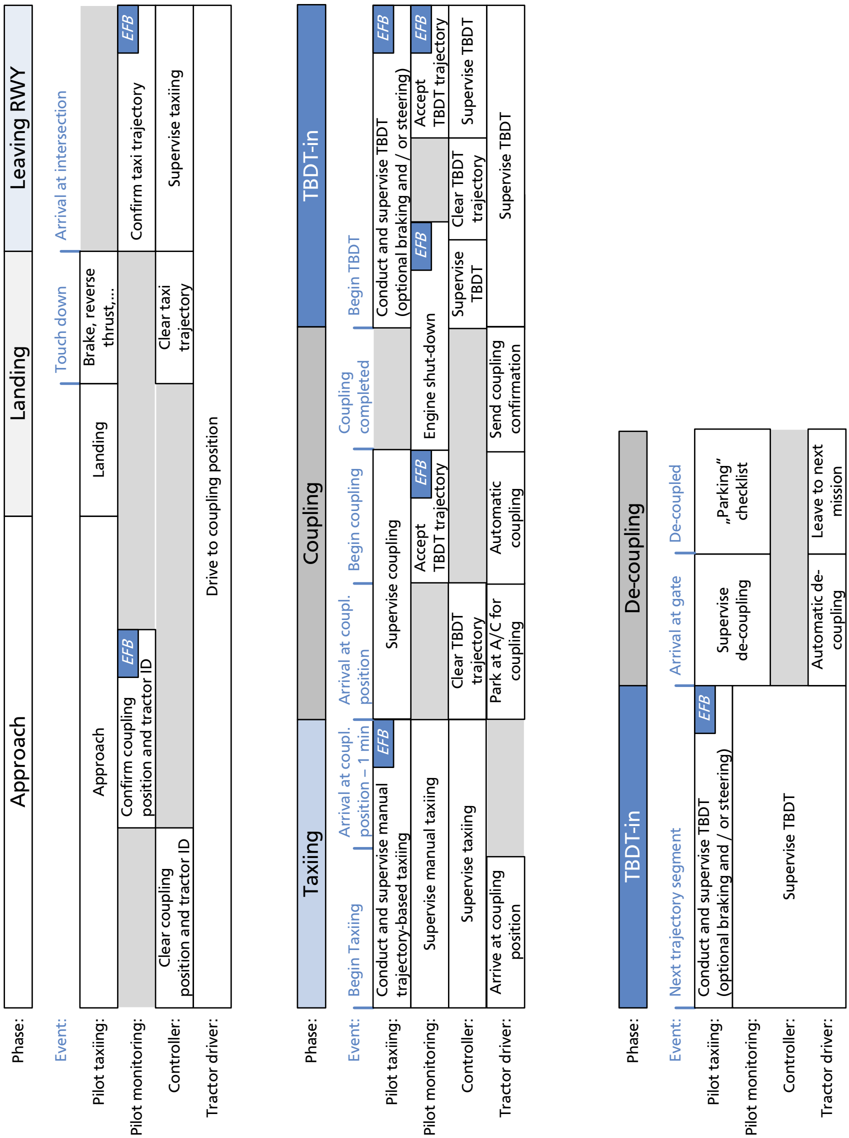

Figure C.1.: Swim-lane diagram of TBDT-in process (TBDT-related tasks only)

D Participating Pilots of Expert Interviews

Table D.1.: Overview of pilots participating in the expert interviews

Pilot ID	Type Rating	TaxiBot experience	Notes
I1	general aviation	aware of concept	human factors professional
I2	Boeing 737	conducted TaxiBot operations	
I3	Airbus A380	no	
I4	Airbus A320	involved in operational planning	
I5	Boeing 777	no	

E Participating Pilots of Pre-Trials in Simulator

Table E.1.: Overview of pilots participating in the pre-trials in the flight research simulator

Pilot ID	Type Rating	Flight hours (commercial)	Rank	Age	TaxiBot experience
P1	-	0	CPL obtained	26	no
P2	-	0	PPL obtained	29	no
P3	Boeing 747-400 / -8	15000	CPT	52	conducted TaxiBot operations
P4	Airbus A380	18000	CPT	53	no
P5	Airbus A380	6900	FO	37	aware of concept

F Participating Pilots of Main Simulator Evaluation

Table F.1.: Overview of pilots participating in the main evaluation in the flight research simulator

Pilot ID	Type Rating	Flight hours (commercial)	Rank	Age	TaxiBot experience
F1	Boeing 737	0	FO	27	aware of concept
F2	Learjet 60	550	CPT	56	no
F3	Airbus A320	13000	CPT	41	no
F4	Airbus A380	10000	CPT	54	aware of concept
F5	Airbus A380	7200	SFO	38	aware of concept
F6	Boeing 747	8000	SFO	36	aware of concept
F7	Boeing 747	15000	CPT	52	conducted TaxiBot operations
F8	Boeing 757 / 767	4000	SFO	30	no
F9	Airbus A320	4800	FO	32	aware of concept
F10	Airbus A320	4800	FO	30	aware of concept
F11	Airbus A380	22500	CPT retired	60	no
F12	Boeing 747	21000	CPT	65	no
F13	Airbus A320	5000	FO	33	aware of concept
F14	Boeing 777	3200	SFO	30	aware of concept
F15	Embraer 190	10000	CPT	39	aware of concept
F16	Boeing 757 / 767	11300	CPT	50	no
F17	Boeing 757 / 767	10000	CPT	45	no
F18	Boeing 757 / 767	10000	CPT	42	no
F19	Boeing 757 / 767	3640	SFO	30	no
F20	Boeing 757 / 767	6000	SFO	39	no
F21	Airbus A320	3250	FO	30	no
F22	Boeing 757 / 767	4800	SFO	27	no
F23	Boeing 757 / 767	500	FO	31	no
F24	Boeing 757 / 767	10000	CPT	47	no

G Dataset Recorded in Main Simulator Evaluation

Table G.1.: Recorded data during the main simulator evaluation

Type	Unit	Symbol if mentioned in text
Time	s	t
Actual distance east	m	
Actual distance north	m	
Actual latitude	°	lat
Actual longitude	°	lon
Actual heading	rad	Ψ
Actual ground speed	$\frac{m}{s}$	GS
Actual acceleration	$\frac{m}{s^2}$	a
Target* distance east	m	
Target* distance north	m	
Target* ground speed	$\frac{m}{s}$	GS_{trg}
Planned** ground speed	$\frac{m}{s}$	GS_p
Planned** maximum ground speed	$\frac{m}{s}$	
Planned** distance east	m	
Planned** distance north	m	
Planned** distance along trajectory	m	s_p
Planned** heading	rad	Ψ_p
Planned** curvature	$\frac{1}{m}$	κ_p
Set automation mode	–	
Actual automation mode	–	
Perpendicular position error	m	$d_\perp$

Position error along trajectory	m	Δs
Heading error	rad	$\Delta\Psi$
Feed forward steering angle	rad	Φ_{fw}
Fatigue limit of nose gear	N	F_{max}
Trajectory segment counter	–	
Applied steering angle	rad	Φ
Applied force	N	F
Manual brake phase indicator	–	
Left brake pedal deflection	rad	
Right brake pedal deflection	rad	
Ruder deflection	%	
Last measured reaction time	s	$t_{r,i}$
Indicator if object is visible	–	
Reaction type to last object	–	
Latitude of last object	°	
Longitude of last object	°	

* *Target* refers to the target value for the current time step.

** *Planned* refers to the initially planned value for the trajectory segment closest to the actual position.

H Applied Effect Size Calculations and Interpretations

Even significant test results may have a low relevance. Especially when sample sizes are large, significance can be reached even though the differences are low compared to the "noise" of the outcome [Fie16, pp. 79]. In this thesis, the effect sizes are calculated by Pearson's correlation coefficient. Effect sizes are calculated for the Wilcoxon signed rank test and the factorial repeated measures analysis of variance (ANOVA) as presented in the following subsections.

H.1 Calculating the Effect Size for Wilcoxon Signed Rank Test

$$r_{\text{effect size}} = \frac{z}{\sqrt{n_{\text{Observations}}}} = \frac{z}{\sqrt{n_{\text{Pilots}}}} = \frac{z}{\sqrt{48}}\ .$$

H.2 Calculating the Effect Size for Factorial Repeated Measures ANOVA

$$r_{\text{effect size}} = \sqrt{\frac{F}{F + df_R}} = \sqrt{\frac{F}{F + n_{\text{Pilots}} - 1}} = \sqrt{\frac{F}{F + 23}}$$

with df_R for the degree of freedom of the residual.

H.3 Interpretation of Effect Sizes

The calculated effect sizes are interpreted in this thesis according to Cohen [Coh92, p. 157]:

- $r_{\text{effect size}} = 0.10$: small effect
- $r_{\text{effect size}} = 0.30$: medium effect
- $r_{\text{effect size}} = 0.50$: large effect.

I Descriptive Results of Additional Measurements during Main Simulator Evaluation

I.1 Raw Nasa Task Load Index

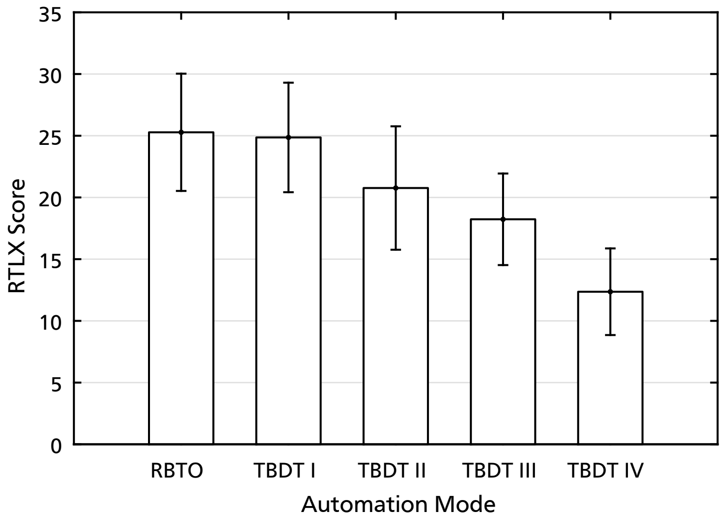

Figure I.1.: Subjective workload ratings by the raw NASA task load index (mean and 95 % CI)

I.2 Additional Likert Scale Questions

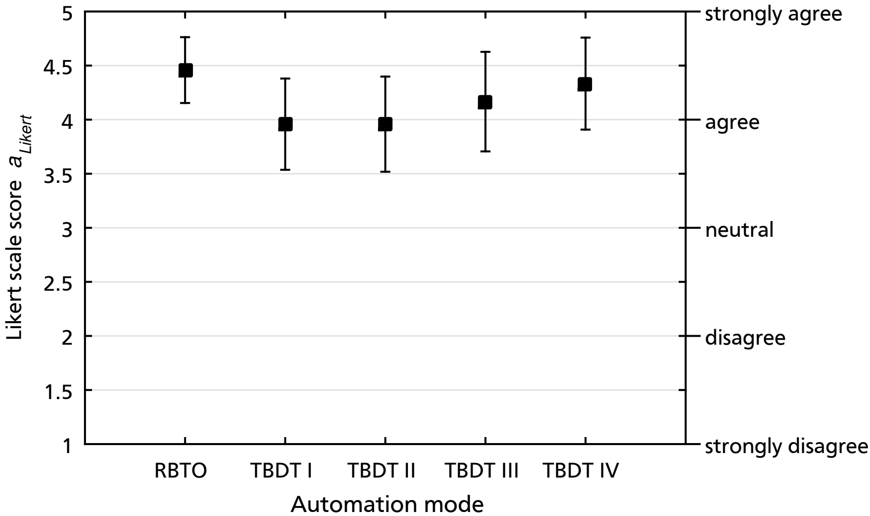

Figure I.2.: Likert scale rating regarding statement "I feel mentally ready for take-off." (mean and 95 % CI)

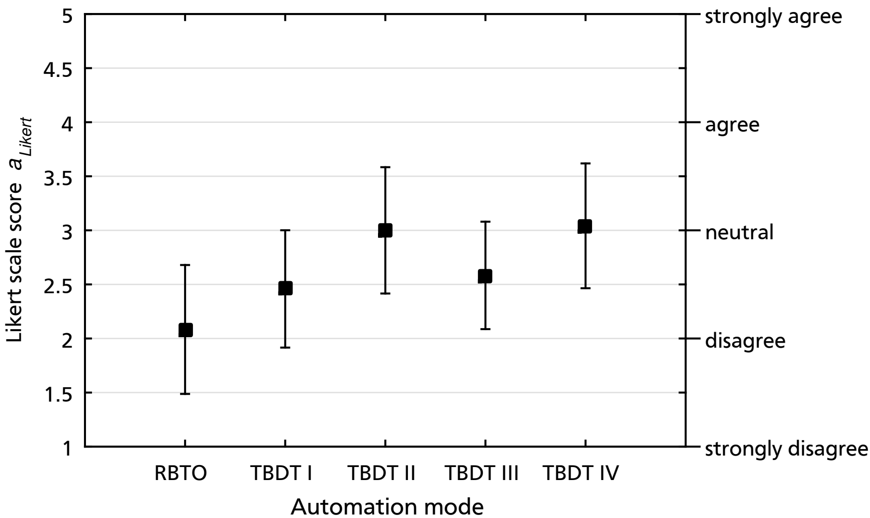

Figure I.3.: Likert scale rating regarding statement "I would rather perform more tasks manually." (mean and 95 % CI)

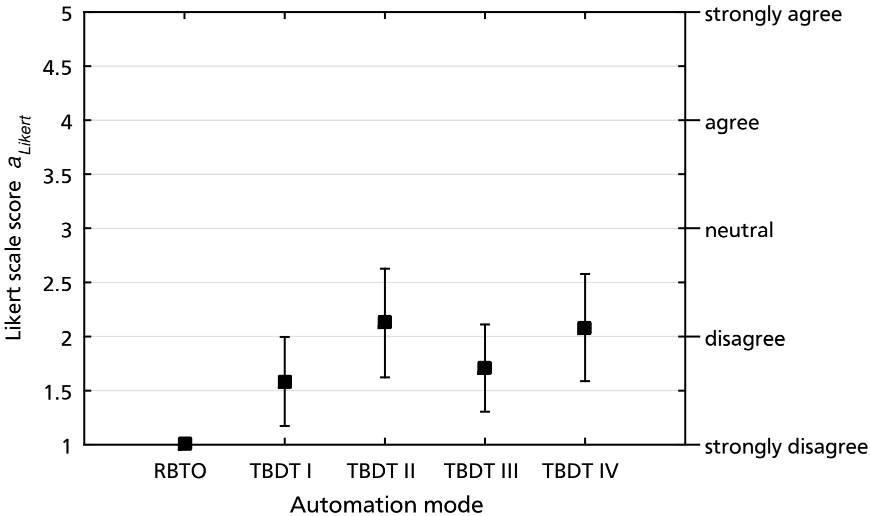

Figure I.4.: Likert scale rating regarding statement "I feel patronized by the system." (mean and 95 % CI)

I.3 Subjective Ranking of Modes

At the end of all trials, pilots were asked to conduct an individual ranking of the modes assuming they could chose how future taxi operations should be implemented.

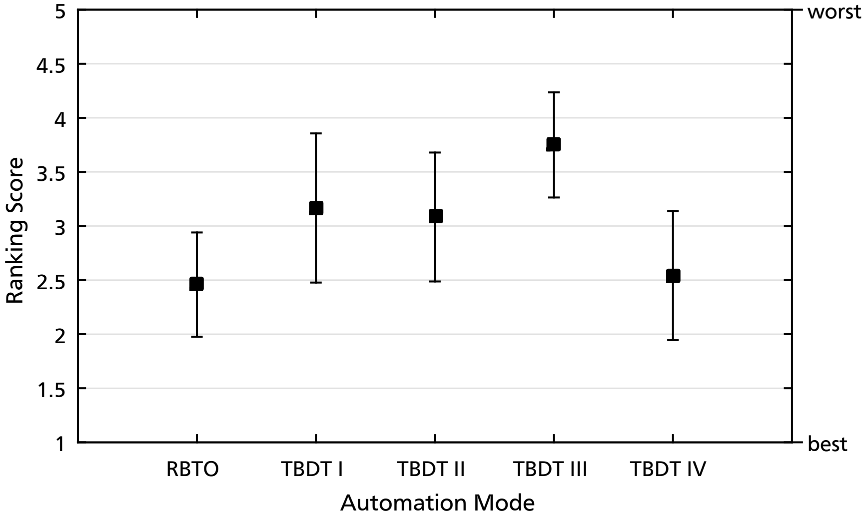

Figure I.5.: Ranking values of the automation modes (mean and 95 % CI)

J Free Text Comments of Participating Pilots of Main Simulator Evaluation

The following comments are copied from the questionnaires with only minor spelling corrections applied.

J.1 Comments on RBTO

General Comments on RBTO

- Automatisierungsgrad erfordert hohe Konzentration, dadurch etwas geringeres Aufmerksamkeitsbewusstsein (Kegel).
- Man behält das Gefühl der "Pilot in Command" zu sein.
- Beim manuellen Rollen keine Zeit, sich mental auf Take-Off vorzubereiten.
- Aktuelle IST-Situation – kann bei großen Flughäfen mit komplexen Rollfreigaben sehr viele Kapazitäten binden.
- Größte Arbeitsbelastung, aber auch höchste Autonomie.
- Gewohnte Aufgabe, angenehm, die Geschwindigkeit selber zu bestimmen.
- Es ist möglich an erfahrungsgemäß kritischen Punkten die Geschwindigkeit zu reduzieren und sich an den Verkehrsfluss anzupassen.
- Deutlich weniger ermüdend.

Explanations for Good Ranking of RBTO

- Bin daran gewöhnt.
- Gewohnheit.
- Spaß-Faktor.
- Macht am meisten Spaß.
- Ich halte es für wichtig, dass der Pilot regelmäßig selbst rollt um der Automation nicht blind zu vertrauen.
- Man bleibt "pilot in command".
- Hab ich schon immer so gemacht (gewöhnt).
- Gelernt ist gelernt :) Routine und Erfahrung bringen Sicherheit.
- Bekannt, unter Kontrolle.

- Gewöhnung, man hat was zu tun.
- Wie TBDT I ohne Ökovorteil.
- Verantwortung und Steuerung bleibt im Cockpit – nicht ermüdend.
- Volle Kontrolle über alle Systeme.
- Sichere eigenständige Durchführung der Aufgabe.

Explanations for Low Ranking of RBTO
- Umweltbelastendste und kapazitätsbindendste Variante.

J.2 Comments on TBDT I

General Comments on TBDT I
- Moving Map hilft für das Situationsbewusstsein für Bremsen und Lenken.
- Schön, weil es ist, wie konventionelles Rollen.
- Triebwerksstart in Modus I schwierig, weil laut Airbus-Verfahren beide auf Display schauen müssen.
- Display sehr einfach (Bremsanzeige).
- Akustisches Signal sollte später kommen, direkt mit der geänderten Soll-Geschwindigkeit.
- Fand ich (fast) am besten.
- Höhere Arbeitsbelastung als beim konventionellen Rollen und Gefahr Bremssignal nicht wahrzunehmen.
- Ich finde, etwas mehr Automatisierung dann doch besser.
- Nicht vertraut mit Simulator.
- Darstellung auf EFB sehr schön und einfach.
- EFB lenkt nicht ab, sondern unterstützt sogar.
- Am aufmerksamsten, außer beim Bremsen.
- Am meisten Spaß gemacht.
- <10 kts empfinde ich als ermüdend.
- Die Zielwerte beim Bremseingriff als Endwerte definieren. Würde weniger ablenken und den manuellen Bremseingriff beschleunigen.
- Zielgeschwindigkeitsanzeige wäre hilfreich.
- Speed-Indicator sollte lieber beim PFD positioniert sein.
- Speed Indicator etwas zu dynamisch.
- Verzögerungen sehr stark. Würde man nur in Ausnahmefällen so machen.
- Nichts halbes, nichts ganzes.
- Dann würde ich es lieber ganz selbst machen.

Explanations for Good Ranking of TBDT I

- Ökonomisch.
- Optimale Unterstützung des TBDT, aber dennoch genug manuelle Kontrolle.
- Man ist voll dabei, da man agiert und nicht reagiert.
- Ökonomische Vorteile. Bei manuell/manuell kann man besser auf einzelne Situationen reagieren.
- Aufmerksamkeit auf die Aufgabe "Taxi" am höchsten.
- Ökologisch und wirtschaftlich sinnvoll.
- Ähnelt am ehesten dem gewohnten, man bleibt aufmerksam.
- Erfüllung der Aufgabe und dabei immer Teil des Systems.
- Systemintegration.
- Möglichst viel eigene Kontrolle.

Explanations for Low Ranking of TBDT I

- Größte Ablenkung durch Bremsanweisungen.
- Da kann man es auch selber machen mit dem Rollen (außer Treibstoffeffizienz).
- Kaum Vorteil zum manuellen Rollen.
- Zusätzliche Arbeitsbelastung im Vergleich zum manuellen Rollen.
- Der Trajektorie incl. Speed manuell zu folgen, erfordert mehr Kapazität als herkömmliches Rollen.
- Teilabgabe der Aufgabe erhöht den Stresslevel.

J.3 Comments on TBDT II

General Comments on TBDT II

- Sehr gutes Situationsbewusstsein, da man weniger vom EFB abgelenkt ist.
- Moving Map hilft, den Rollprozess besser einzuschätzen.
- War noch mit der ungewohnten Steuerung beschäftigt, habe den meines Wissens vorletzten Diamanten verpasst.
- Die Bremsvorgänge waren kaum nachvollziehbar und kamen sehr plötzlich. Fühlte mich manchmal nicht "im Loop".
- Lenkeingaben schwierig, da man die Geschwindigkeit schlecht abschätzen kann, mit der der TaxiBot in die Kurve geht.
- Man weiß nicht genau, wann verzögert / beschleunigt wird.
- Eigentlich eine gute Kombination, denn der Fokus kann dort bleiben, wo er benötigt wird: vorne, draußen.
- Etwas höhere Grundbelastung, dafür keine Gefahr, ein Signal zu überhören.
- Vertrauen in System der Geschwindigkeitsregelung notwendig.
- Grund für Bremsungen nicht ersichtlich.
- Manchmal in den Kurven zu sehr abgebremst.

- Wann/wie/wo gebremst wird passt nicht immer zum Lenkausschlag.
- Sehr ermüdend und anstrengend bei allen Geschwindigkeiten.
- Farbliche Anpassung der Handlungsanweisung wenn direkte Handlung gefordert.
- Angenehmer, mehr Zeit zum rausschauen.
- Automatisches Bremsen schafft viel Kapazität, um sich auf Umgebung zu konzentrieren.

Explanations for Good Ranking of TBDT II

- Weniger Ablenkung durch EFB, ermöglicht dennoch die Kontrolle des Flugzeuges nicht komplett abzugeben.
- Für mich die beste Version. Sie zwingt den Piloten, den Fokus zu behalten.
- Man hat das Steuern noch selber in der Hand, lässt einen auch aufmerksamer bleiben.
- Wenig Workload, aber eine Aufgabe -> führt zu mehr Aufmerksamkeit.
- Brake auto bindet mich ein, zusätzliche Instrumente zu beobachten.
- Erleichterung spürbar (genauso bei TBDT III).
- Geringste Beeinträchtigung.
- Wenn der Trajektorie gefolgt werden soll, ist das automatische Bremsen sehr hilfreich. Wesentlich größerer Kapazitätsgewinn als Auto Steer.

Explanations for Low Ranking of TBDT II

- Im Falle einer Notbremsung verliert man Zeit, um mental auf manuelles Bremsen umzuschalten.
- Die anspruchsvollste Aufgabe verbleibt beim Piloten. Die Automatisierung ist wenig nachvollziehbar.
- Ungeschickte Aufteilung des Automatismus, da Geschwindigkeit beim Lenken unvorhersehbar.
- Erhöhte Aufmerksam ist erforderlich. Bei manuell/auto wird viel Kapazität gebunden um die Automatik "vorherzusehen"

J.4 Comments on TBDT III

General Comments on TBDT III

- Zielgrößenangabe wäre hilfreich.
- Displaydarstellung (Weiß) + Audiosignal sehr hilfreich.
- Entspannt.
- Zur Anzeige: hätte gern mehr Infos zum "Trendvektor".
- Vorteil: Bodennavigation entfällt.

- Das System rollte ab und zu anders, als ich dies tun würde (nicht auf Centerline), hier würde ich mir manuelle Lenkeingriffe wünschen.
- Laut Lufthansa-Regulation ist es verboten, mit Auto-Throttle zu fliegen, wenn der Auto-Pilot off ist (Mischautomatisierung problematisch).
- Position des EFB ist hier entscheidender für die Praxistauglichkeit.
- Im Betrieb potentielle Gefahr, bei Vorbereitung auf Start die Aufforderung für den Bremsvorgang zu überhören/übersehen.
- Die Zielgeschwindigkeit vielleicht. früher anzeigen.
- Beim Bremsen schwankte der Curser sehr.
- Grund für Bremsung nicht ersichtlich.
- Man ist nur noch Beobachter, das ist unschön.
- Sehr einfache Bedienung. Nur überwachende Funktion.
- Sehr gute Unterstützung durch EFB. Schafft Raum für andere Tätigkeiten.
- Ist gut.
- Langsame Geschwindigkeit empfand ich als ermüdend.
- Bremsanzeige braucht viel Aufmerksamkeit, wenn aktiv.
- Nicht ausreichend auf Take-off vorbereitet wegen parallelem Briefing/ Take-off Performance/Checkliste.
- Aufgrund geringer Arbeitsbelastung müde geworden.
- Verbesserungsvorschlag Speed Indicator: Anzeige auf PFD oder ND. Tatsächliche wird bereits angezeigt. Zielgeschwindigkeit soll dann daneben in cyan stehen. Bei starker Abweichung soll Zielgeschwindigkeit mit Rahmen blinken.
- Ich würde keinen TW-Start während des Rollens vornehmen – 4 Augen Prinzip. Evtl. schon, wenn ein Schlepperfahrer vorhanden ist.
- Hier sehr gute EFB-Position. Bei 757/767 nicht so gegeben.

Explanations for Good Ranking of TBDT III

- Eigene Entscheidung zur Bremsung/Notbremsung.
- Habe gerne selber die Kontrolle über die Bremsen, der Moment "Bremst es oder nicht?" kann zu lange dauern.
- Überlässt dem Piloten die Kontrolle der Geschwindigkeit.

Explanations for Low Ranking of TBDT III

- Zu große Ablenkung durch EFB, Kontrollabgabe an Automatisierung.
- Man ist geneigt, die Aufmerksamkeit falsch zu setzen.
- Sicherheitsrisiko bei Übersehen des Bremssignals.
- Die Steuerung gebe ich ungern ab, weil der Aufmerksamkeitspegel sinkt. Man fühlt sich an den Rand des Regelkreises gedrängt.
- Teilautomatisierung erhöht evtl. Arbeitsbelastung.

- Dann lieber manuell.
- Aufmerksamkeit zu sehr auf EFB.
- Wenn man schon nicht selbst lenkt, so ist eine volle Automation der höchste Grad an Sicherheit – so lange man “overrulen” kann.

J.5 Comments on TBDT IV

General Comments on TBDT IV

- Sehr gutes Situationsbewusstsein möglich.
- Man neigt dazu, seine Konzentration zu verlieren und die Kontrolle des Flugzeuges komplett an das automatisierte System abzugeben.
- Triebwerksstart während Rollen sehr einfach.
- Man lässt sich treiben, man achtet aber auch nicht mehr so genau auf das Taxiing.
- Eigentlich wäre dieser Modus optimal.
- Ich hätte ab und zu evtl. etwas anders gelenkt.
- Nur ab und zu wären korrigierende Lenkeingriffe sinnvoll.
- System muss sehr hohe Zuverlässigkeiten haben, da bei fehlendem Vertrauen ein hoher Überwachungsaufwand entsteht.
- Farbliche Darstellung von Abweichungen von SOLL zu IST Geschwindigkeit wäre hilfreich um Fehler zu erkennen (weiße Hinterlegung, wie in manuellen brake-Modi, nur ohne Ton).
- Ermüdend.
- Man hofft die ganze Zeit, dass die Automatisierung alles richtig macht.
- Höchster Automatisierungsgrad => Gefahr der Ablenkung und des "Sich-absolut-sicher-Fühlens".
- Man wird unkonzentriert.
- Man verliert die Aufmerksamkeit.
- Der Blick schweift ab.
- Weniger ermüdend als Auto Brake, aber dennoch ermüdend, besonders < 10 kts.
- Vertrauen ins System muss vorhanden sein, sonst führt das zu mehr Arbeitsbelastung.
- Ich würde mich sicher fühlen, aber erst wenn ich mich an den Modus gewöhnt habe.

Explanations for Good Ranking of TBDT IV

- Schafft den größten Freiraum (mental).

- Größte Arbeitsentlastung. Es blieb noch genug Kapazität, um im Loop zu bleiben.
- Größte Entlastung bei hoher Zuverlässigkeit.
- Erhöhte Kapazität des Piloten, ist am besten planbar.
- Entlastung, Ökoeffizienz.
- Höchste Entlastungsstufe.
- Schafft insgesamt die meiste Kapazität, um sich auf Verkehr etc. zu konzentrieren.
- Sinnvolle Abnahme einer Aufgabe.
- Wenn System ausreichend zuverlässig: Erhöhung der Sicherheit, Reduzierung der Workload.
- Größte Entlastung, aber Vertrauen ins System notwendig.
- Wenig Workload.
- Arbeitserleichterung, mehr Kapazitäten für andere Aufgaben.

Explanations for Low Ranking of TBDT IV

- Finde ich eher gefährlich wegen Nachlässigkeit. (Handschrift anschließend nicht erkennbar.)
- Einschläfernd. Aufmerksamkeit geht verloren. Ist man als Pilot noch in der Lage, bei Systemfehler selbst zu steuern?!
- Mental sehr anstrengend.