Technische Universität München
TUM School of Engineering and Design

Designing Safe Transition Phases with Minimal Risk Maneuvers of Automated Vehicles

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Vollständiger Abdruck der von der TUM School of Engineering and Design der Technischen Universität München zur Erlangung des akademischen Grades eines

Doktors der Ingenieurwissenschaften (Dr.-Ing.)

genehmigten Dissertation.

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Prüfende der Dissertation:
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Die Dissertation wurde am 20.11.2023 bei der Technischen Universität München eingereicht und durch die TUM School of Engineering and Design am 03.09.2024 angenommen.

Thank you

I am pleased to have reached the point where I can express my gratitude. First and foremost, I am incredibly grateful to Prof. Klaus Bengler for granting me the opportunity to complete my doctorate at the Chair of Ergonomics. The thanks not only go to the opportunity but, above all, to the support, the freedom for research, and the high trust in me and my work. I am particularly grateful for the "guardrails" that I received in discussions during my doctorate – they did not throw me off track and ultimately brought me safely to the finish line. I would also like to thank Prof. Trivedi and Prof. Betz for the exciting discussions and the willingness to be my examiners. I thank Prof. Bogenberger for accepting the examination committee chair.

At this point, I would like to express my thanks to Prof. Satoshi Kitazaki and all the partners of the German-Japanese research project "CADJapanGermany: HF." The project offered me the unique opportunity to work with scientists across the globe. In this context, I would especially like to thank the doctoral students who had to put up with me at every regular appointment, and on our trips to Japan. It was a wonderful time, and your perspectives have shaped me and my work.

The Chair of Ergonomics offers an exceptional environment that I will miss. The friendly interaction and willingness to help led me to exchange ideas with everyone, and I can only say a big thank you to every colleague. However, I have to mention some names explicitly. Thanks to Luis, who constantly challenged me as a sparring partner (scientifically, of course) and accompanied me through the day with much humor. Thank you, Niklas, for the numerous discussions on and off work and for creating lasting memories. Thanks to Yucheng, who encouraged me to pursue a doctorate and gave me survival tips, especially at the beginning of my career. Thanks to my office colleague Julia for the everyday exchange and the many laughs. Thank you, Malaika, for the thoughtful discussions at the end of my thesis and your advice on work and life.

My family deserves thanks that I cannot express in words. From my parents, Seyfettin and Fatma, to my beloved siblings, Duygu and Berkay, who always have supported me unconditionally. I can't thank my wife, Kübra, enough for always having my back and constantly motivating and pushing me. My son, Yunus Emre, always reminded me that there are more important things in life and, fortunately, challenged me in other areas.

Abstract

Automated vehicles offer numerous advantages, with user benefits taking precedence. Current developments and forecasts indicate that introducing highly automated vehicles is a matter of time rather than technical feasibility. Recent research is dedicated to the challenge of assigning the driving task primarily to an automated system, thereby allowing users to engage in other activities. An integral function in this context is the minimal risk maneuver (MRM). The automation deploys this maneuver to achieve a safe condition in the event of a system limit. This is referred to as a transition phase since the automation level degrades, and the journey should be continued in manual mode. The literature research for this work has revealed that the desired condition for the vehicle is coming to a standstill, preferably on the hard shoulder. However, the literature also shows that the driver is not entirely relieved of the driving task during this transition phase. This work delves explicitly into this phase and examines conditions under which collision risk can be reduced.

Four empirical studies, which systematically build on each other, were conducted to answer the research question. In the first study, test subjects evaluated various MRMs in a video survey to determine whether the drivers' intentions contradict those of automated vehicles. The second study examined whether control authority, i.e., allowing or blocking driver interventions, reduces the collision risk. In the third study, a new human-machine interface concept was developed and tested to support driver decision-making in this phase. In the fourth and final study, the transition phase of automated vehicles with MRMs was observed from the perspective of the surrounding manually driven traffic and evaluated in terms of controllability.

The results across all studies indicate a discrepancy between the maneuvers preferred by drivers and those performed by automated vehicles. This discrepancy is mainly responsible for drivers intervening in the transition phase and resolving the situation manually. The collision risk can be mitigated through targeted measures and under certain circumstances, such as supporting driver decisions based on traffic in neighboring lanes. Eventually, the goal of this work was to design the transition phase with an MRM, which can be found as the "Transition Protocol." This protocol combines the results and conditions examined and answers the research question. In the future, these findings should be considered alongside technical aspects when introducing automated vehicles with an MRM function to ensure safe use.

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Acronyms

AV	Automated Vehicle
AoM	Announcement of Maneuver
ALKS	Automated Lane Keeping Systems
cHUD	Contact Analog Head-Up Display
DDT	Dynamic Driving Task
EM	Emergency Maneuver
EES	Energy Equivalent Speed
ETTC	Enhanced Time To Collision
FMS	Failure Mitigation Strategy
HMI	Human-Machine Interface
MAIS	Maximum Abbreviated Injury Scale
MRC	Minimal Risk Condition
MRM	Minimal Risk Maneuver
NDRT	Non-Driving Related Task
ODD	Operational Design Domain
OEDR	Object and Event Detection and Response
RtI	Request to Intervene
TIV	Time Inter-Vehicular
TTC	Time To Collision
UNECE	United Nations Economic Commission for Europe

1 Introduction

1.1 Background

Automated driving has developed rapidly over the last few years, but pursuing this ambitious goal dates back to 1925 (Janai, Güney, Behl, & Geiger, 2020). It took approximately 40 years since the invention of the automobile by Carl Benz in 1886 to demonstrate the driverless vehicle called "American Wonder" by Houdina Radio Control Co. The idea was to remotely control it via radio waves from another following vehicle along Broadway in New York. Unfortunately, the demonstration had to be ended due to a collision with a passenger-filled vehicle (Time Inc., 1925). The following years continued the approach of remote-controlled or infrastructure-based navigation of autonomous vehicles. The ideal vision of an automated vehicle (AV) today should fulfill the origin of the term *autonomous*, which can be translated to "self-governing" or "self-sufficient." The prototype that marks a step towards this vision was developed by Ernst Dickmanns' team at the Bundeswehr University of Munich in Germany and was called "Versuchsfahrzeug für autonome Mobilität und Rechnersehen (VaMoRs)" (Wishart, 2022). His team was also part of the European project "PROgraM for a European Traffic with Highest Efficiency and Unprecedented Safety (PROMETHEUS)" (Nagel, Struss, Trottenberg, Menzel, & von Seelen, 2008). The project achieved a milestone in the history of automated driving in 1995 with the first long-distance drive from Munich, Germany, to Odense, Denmark, with around 95% of automated driving (Janai et al., 2020). Over the next nearly 30 years, many research projects involving automotive manufacturers and tech companies were conducted. This symbiosis has driven the development of driver assistance systems to the point that we now find them in commercially available vehicles (Chan, 2017, p. 2). Nonetheless, what motivates this extensive process for nearly 100 years?

First, automated driving is expected to contribute to the solution of various problems (Chan, 2017, pp. 4-5). Two were already named under the premise of an ideal world for AVs since they are part of the acronym PROMETHEUS: efficiency and safety. Against the backdrop of a rising population and urbanization, relieving traffic congestion, saving time, and preventing collisions is vital. Further, enhanced mobility, especially for users unable or no longer able to drive, is hoped. Moreover, increased comfort and productivity are promised while intelligent systems overtake the driving task. Alongside infrastructure changes, including resource savings and increased green spaces, these factors also play a significant role in addressing one of the major challenges of our century: sustainability. Automated driving serves as a pivotal tool in reducing emissions by decreasing the necessity for private vehicle ownership, making mobility more resource-efficient. These are justifiable visions that are difficult to achieve, and the main challenge is to fit an AV into a traffic system made for manual driving.

Second, the motivation is not solely goodwill. According to the McKinsey Center for Future Mobility, passenger cars with automated driving systems may generate \$300 to \$400 billion in revenues by 2035 (Deichmann et al., 2023). Furthermore, the sales figures of passenger vehicles by 2030 and 2035 are estimated for three scenarios, i.e., *delayed*, *base*, and *accelerated* (see Figure 1.1). The results show that the proportion of vehicles equipped with Level 3 or higher automated driving systems has a share between 4% and 20% by 2030 and between 17% and 57% by 2035. Even in the worst-case scenario, these systems are expected to be introduced in the current traffic system by 2030 at the latest.

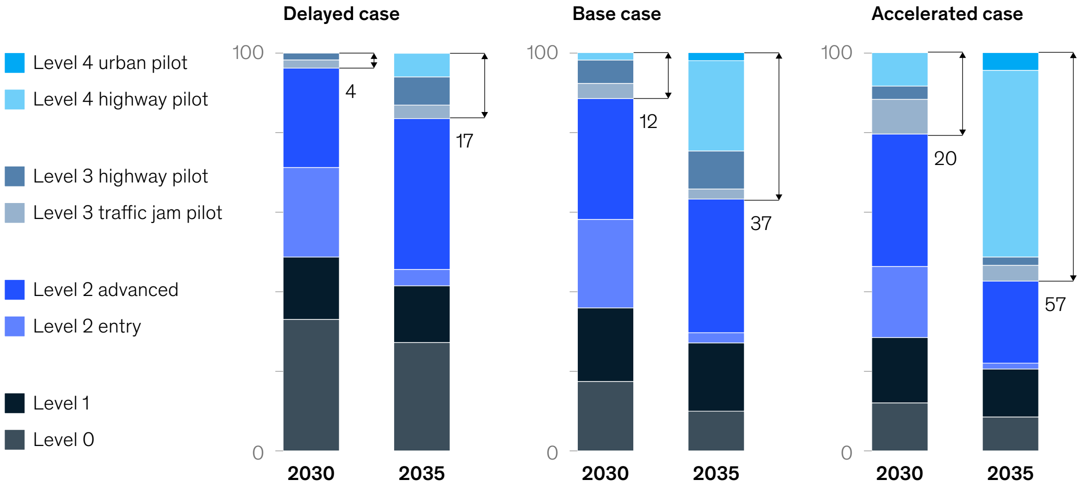

Figure 1.1: Estimated proportions (0% to 100%) of sold passenger vehicles equipped with automated driving systems by 2030 and 2035. The automation classification, i.e., Levels 0 to 4, refers to SAE International (2021) (Deichmann et al., 2023).

The addressed levels of automation refer to the taxonomy by SAE International (2021), in which manual driving is defined as Level 0. As the level of automation increases, the role of the driver changes. The highest level of automation, i.e., Level 5, is independent of user input during the drive to reach its final destination. For all other levels, the human driver or user of an automated system must perform specific tasks while traveling. At Level 3, an important change takes place that is a strong selling point for these systems: the driver can hand over the driving task to the AV and is allowed to engage in a non-driving related task (NDRT), e.g., eating and drinking, resting, and reading (Naujoks, Befelein, Wiedemann, & Neukum, 2017). Yet, the driver must take over and is responsible for achieving a minimal risk condition (MRC) within a time budget whenever the automated system cannot continue its trip. This take-over process was intensely researched from a human factors point of view and showed the dangers and some potential countermeasures (see Chapter 1.3). Vehicles at Level 4 automatically conduct a minimal risk maneuver (MRM) to achieve an MRC without driver input. Nevertheless, vehicles at Level 3 can but do not have to be equipped with MRM functionality as defined by SAE International (2021). However, Level 3 systems in Japan, such as the "Traffic Jam Pilot" by Honda, must automatically conduct an MRM as a safe stop (Honda Motor, 2020; The Japan Times, 2021).

Therefore, the new transition process with MRMs must be explored to successfully introduce Level 3 and 4 systems. As the next chapter shows, the human as a driver or user of the system is still required during this process.

1.2 State of the Art of Minimal Risk Maneuvers

This chapter provides an overview of the current and most essential taxonomies, regulations, and other literature that describe MRMs or at least MRCs. The focus is on the strategic aspect of the transition phase, and the goal is to point out the driver's role. Aspects of the technical functionality are not described here and can be found, e.g., at Ackermann and Winner (2020), Homolla and Winner (2022), and Popp, Ackermann, and Winner (2022).

Taxonomy of SAE International

The taxonomy of driving automation systems from SAE International (2021) has been widely used since its introduction in 2014. The collaboration with the ISO Technical Committee TC204 (WG14) resulted in the current and fourth version of the J3016, which is technically equivalent to ISO/SAE PAS 22736:2021 (International Organization for Standardization, 2021). Although the collaboration with ISO gives the document the character of a standard, SAE describes the taxonomy as non-normative, and the classifications should be understood more as descriptive and informative. In addition, it is limited to systems that perform some or all of the driving tasks on a sustained basis. The dynamic driving task (DDT) includes real-time operational and tactical tasks and excludes strategic ones like trip planning. Thus, it distinguishes itself from assistance functions purely warning, informing, or temporarily intervening in the driving task, such as active safety systems. Functions of driver assistance and automation systems can be described and classified holistically together with the Principles of Operation by Gasser, Frey, Seeck, and Auerswald (2017), which will be discussed in the next section.

The taxonomy consists of six levels, and manual driving is set as Level 0, i.e., the vehicle cannot perform the DDT on a sustained basis (see Table 1.1). Drivers still perform a part of the DDT until Level 2. If the system can overtake the longitudinal or lateral control, it is classified as Level 1. The combination of systems that control both directions is set to be Level 2. However, drivers must constantly monitor the system to detect upcoming events and objects. Drivers are relieved from this sub-task called object and event detection and response (OEDR) and can engage in an NDRT from Level 3 onward. Vehicles overtake the DDT at Levels 3 and 4 within limited operating conditions, called the operational design domain (ODD). Whenever the automated system is prevented from continuing its trip, the driver is expected to either achieve an MRC or continue driving manually. This changes for Level 4 systems since the system represents the fallback level, and drivers are no longer required to automatically achieve an MRC.

Table 1.1: The six levels of driving automation adapted from SAE International (2021).

		DDT[1]			
Level	Name	Sustained Vehicle Motion Control[2]	OEDR	DDT Fallback	ODD
0	No Driving Automation	Driver	Driver	Driver	n/a
1	Driver Assistance	Driver and System	Driver	Driver	Limited
2	Partial Driving Automation	System	Driver	Driver	Limited
3	Conditional Driving Automation	System	System	Driver	Limited
4	High Driving Automation	System	System	System	Limited
5	Full Driving Automation	System	System	System	Unlimited

[1] The DDT does not include strategic aspects of the driving task, such as determining destination(s) and deciding when to travel. [2] Lateral and Longitudinal

The term MRM is not specified in the taxonomy and is always referred to as MRC achievement. In case of a system failure or leaving the ODD, the targeted MRC is defined as follows:

> A stable, stopped condition to which a user or an ADS may bring a vehicle after performing the DDT fallback in order to reduce the risk of a crash when a given trip cannot or should not be continued.
>
> — SAE International (2021, p. 15)

The definition was updated in the latest version from 2021 by specifying the condition as a *stable, stopped* one. This includes standstills in the vehicle's own and shoulder lane.

The primary difference between Level 3 and 4 systems is not only the latter system's capability to automatically achieve an MRC but rather the reliability. It does not prevent features of the Level 3 system from performing an MRM. However, it can not guarantee it under all circumstances within the ODD. One condition under which a Level 3 system may also perform an MRM is the presence of an obstacle-free, adjacent shoulder lane. However, even though Level 4 systems must be designed to automatically achieve an MRC under all conditions within their ODD, drivers may still be required for DDT fallback. In fact, Level 4 systems do not preclude the possibility of completing only parts of the journey at this level (called the *sub-trip feature*), thus providing for the vehicle's operation by a driver. In this case, the transition phase starts with a prompt to the driver to overtake the driving task. In contrast, this prompt differs from the request to intervene (RtI) for Level 3 vehicles. Subsequently, the AV automatically achieves an MRC if the driver does not respond within a given time. The taxonomy provides flexibility in the design of the transition phase regarding this issue by stating the following:

> However, a Level 4 or 5 ADS need not be designed to allow a user to perform DDT fallback and, indeed, may be designed to disallow it in order to reduce crash risk.
>
> — SAE International (2021, p. 11)

Therefore, driver take-over or intervention can be suppressed for the sake of safety without specifying the circumstances.

The MRM requires the automated driving system to be functional. Otherwise, a failure mitigation strategy (FMS) is deployed to bring the vehicle to a standstill in case of rare catastrophic events. Level 3 and 4 systems can be equipped with this functionality since it is subordinate to the vehicle and not the automation.

Principles of Operation of BASt

The Federal Highway Research Institute (BASt) in Germany introduced five levels of automation in 2012 (Gasser et al., 2012), which influenced the SAE taxonomy and led to adjustments, such as adding the sixth level of *Full Driving Automation (Level 5)*. The BASt and SAE J3016 levels were aligned after English translation by the International Organization of Motor Vehicle Manufacturers (OICA) (SAE International, 2021, p. 41). Here, too, a take-over request to the driver and the absence of a reaction precede the execution of an MRM. An MRC is a stationary vehicle in the vehicle's lane or on the hard shoulder. Depending on the traffic situation and automation state, the maneuver with the lower risk should be selected and executed. The driver can override the MRM by accelerating, braking, steering, or activating an on/off switch. However, this document describes similar to the SAE J3016 automated driving systems that perform the driving task on a sustained basis, and vehicle functions outside of it are not covered. Therefore, the Principle of Operations Framework was published that decomposes vehicles to their functions for further classification (Gasser et al., 2017; Shi, Gasser, Seeck, & Auerswald, 2020). This framework provides that vehicles can consist of several automation systems, which in turn can consist of different functions (see Figure 1.2).

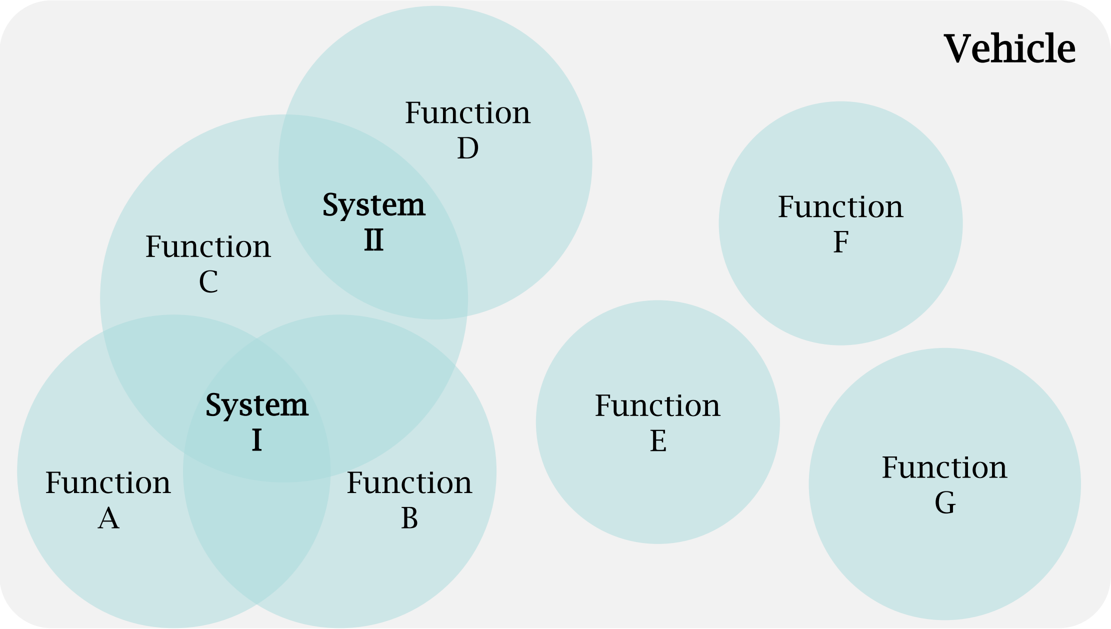

Figure 1.2: Schematic representation of the composition of functions and systems that can be installed in a vehicle according to Gasser et al. (2017) and Shi et al. (2020).

It is limited to functions referring to the layer of vehicle guidance by Donges (2016) and not stabilization or navigation. Functions can be freely combined into one system and are divided into three Principles of Operation (see Figure 1.3).

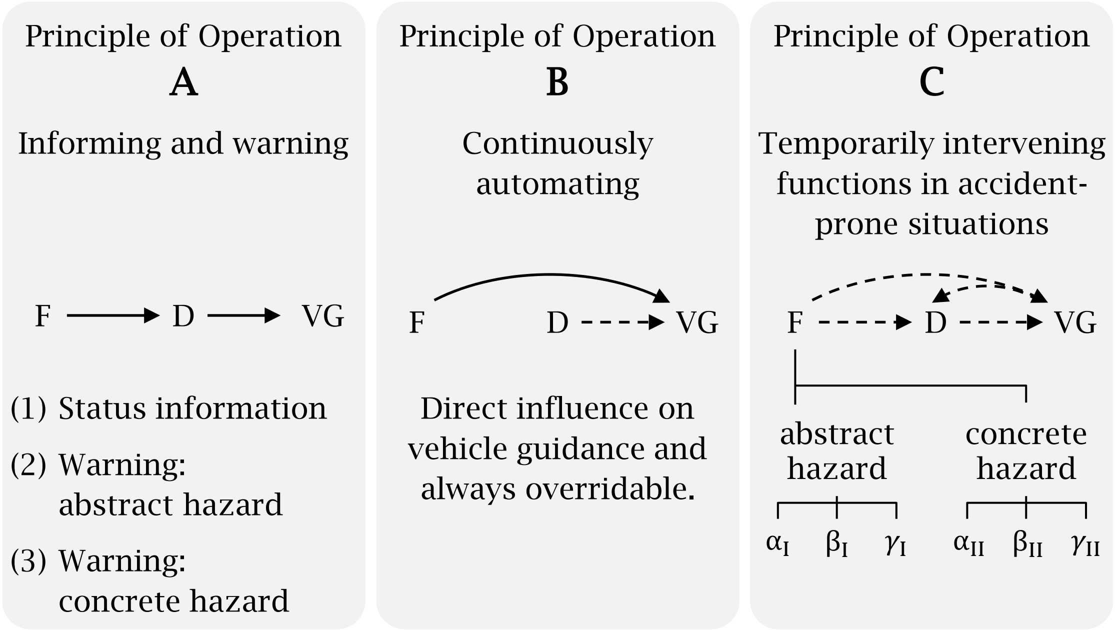

Figure 1.3: The three Principles of Operation. Abbreviations in the impact chain are: Function (F), Driver (D), and Vehicle Guidance (VG). Adapted from Gasser et al. (2017).

The Principle of Operation A covers informing and warning functions that indirectly influence vehicle guidance. The driver receives the information or warning from the function and is responsible for selecting and executing a response regarding vehicle guidance. Functions can transmit status information (e.g., traffic sign recognition), a warning in case of an abstract (e.g., lane departure warning), or a concrete hazard (e.g., forward collision warning). Vehicle control is not as expected in situations with abstract hazards, whereas near-collision situations represent concrete hazards.

The Principle of Operation B covers functions for sustained driving automation for at least a part of the driving task. Therefore, these are corresponding to the SAE Levels 1 to 5. In addition, the framework states that these functions are always overridable.

The Principle of Operation C covers functions that only temporarily intervene in accident-prone situations. It further distinguishes between functions regarding abstract and concrete hazards. Abstract hazards (index I) are accident-prone, and concrete hazards (index II) cause a near-collision situation. The driver or the vehicle cannot resolve the situation due to both hazards. Nevertheless, functions regarding this principle are still designed to be overridable. There are three different levels to which a function can be assigned: α, β, and γ. In case of a concrete hazard, driver action is intensified for α_{II} functions, e.g., intensifying the braking or steering input of drivers. The function at β_{II} temporarily replaces driver intervention, but a take-over is still required afterward (e.g., autonomous emergency braking). At γ_{II}, the function takes over control to avoid the hazard, and a fluent transition to functions at Level β_I or γ_I in the absence of driver take-over proceeds. With an abstract hazard, functions at α_I temporarily intervene and correct the vehicle guidance, e.g., steering assistance if the vehicle leaves the lane. Functions at Level β_I can achieve an MRC in the short term without having a complete overview of the traffic situation and rely on cooperation with other traffic participants. At γ_I, the function entirely takes over control and achieves an MRC. The difference between this MRM function and those of SAE Levels 4 and 5 systems lies in its objective, i.e., the targeted MRC and knowledge of the driver's unavailability.

In summary, vehicles can be equipped with functions that enable continuous automation and achieve an MRC within their ODD. Thus, they would be assigned to the Principle of Operation B. In contrast to the SAE J3016, it is specified here that these functions can always be overridden. Additionally, functions in the Principle of Operation C category are also conceivable concerning MRMs since vehicles can be equipped with multiple functions. Within these temporarily intervening functions, MRMs may occur at the γ_{II}, β_I, or γ_I levels. Yet, all of them are based on the fact that the responsible controller, i.e., the driver or the vehicle, can no longer resolve the situation. Conversely, the strategy is to first push the driver toward fulfilling the driving task. Even if the hazard is concrete and a collision is imminent, a driver reaction is expected at the latest after the function has avoided the hazard (γ_{II}). A failure to respond would initiate another maneuver that achieves either an MRC in short (β_I) or longer-term (γ_I).

United Nations Regulation No. 157

In 2021, a pivotal milestone was reached when the World Forum for Harmonization of Vehicle Regulations (WP.29) of the United Nations Economic Commission for Europe (UNECE) adopted the Regulation No. 157 regarding automated lane keeping systems (ALKS) (UNECE, 2021). The initial regulation specified an operating speed of an ALKS, which can be compared to the SAE Level 3, up to 60 km/h and is the first international binding of its kind (UNECE, 2023b). The current version, i.e., the fourth amendment, includes two main changes: the increase of the operating speed to 130 km/h and the permission of automated lane changes (UNECE, 2023a). The transition demand is defined as the transfer of the DDT from the automated system to the human driver if a planned (known situation in advance, e.g., highway exit) or unplanned event (unknown situation in advance with a high possibility of occurrence, e.g., construction site or lost load from a truck) occurs. An MRM is defined as follows:

> [MRM] means a procedure aimed at minimising risks in traffic, which is automatically performed by the system after a transition demand without driver response or in the case of a severe ALKS or vehicle failure.
> — UNECE (2023a, p. 4)

The aimed condition is further specified as a standstill in the current lane or the most appropriate trajectory if lane markings are missing. A prior lane change is also possible if the targeted area and the circumstances involve fewer risks than the standstill. The maximum deceleration speed is set as 4 m/s^2. The maneuver ends when the standstill is achieved, or the system is deactivated before or during the MRM via:

- steering: exceeding a threshold that includes a force and duration
- holding the steering wheel and braking or accelerating
- holding the steering wheel and the detection of an attentive driver by the system, i.e., drivers gaze at the road, the rear-view mirrors, or move their head towards the driving task

Nevertheless, the system can block driver input upon detection of an imminent collision risk due to this input. In case of any imminent collision risk, the ALKS initiates an emergency maneuver (EM) characterized by a deceleration demand higher than 5 m/s^2. The transition phase resulting from the specifications within the document is visualized in Figure 1.4. It starts with a transition demand escalated after 4 s at the latest. An MRM should start without a driver take-over after 10 s at the earliest. In total, the transition phase takes approximately 14 s when driving at 60 km/h and 19 s at 130 km/h. This duration is mainly influenced by the late start of the MRM and a low deceleration value. In case of severe ALKS or vehicle failures, the MRM can start earlier.

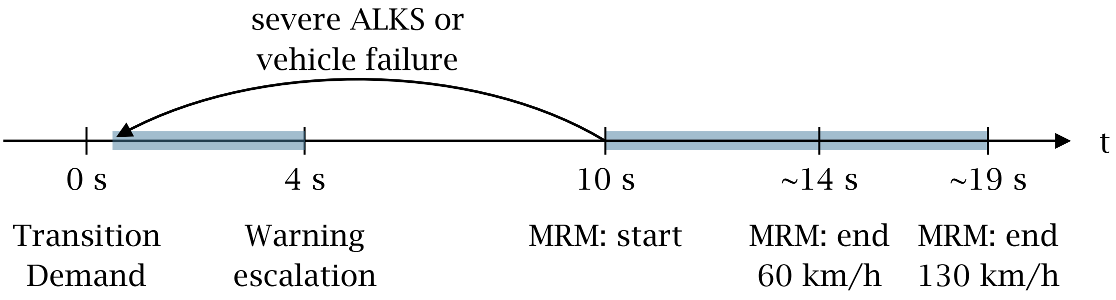

Figure 1.4: The transition phase and calculated durations according to the UNECE (2023a).

Other literature

A white paper from 11 companies describes a framework for developing and validating a safe automated driving system (Wood et al., 2019). These companies – including Aptiv, Audi, Baidu, BMW, Continental, Daimler, Fiat Chrysler Automobiles, HERE, Infineon, Intel, and Volkswagen – published 12 guiding principles referring to vehicles at SAE Level 3 and 4. One of the principles, “Vehicle-Initiated Handover,” requires the system’s ability to automatically achieve an MRC if the user does not follow the take-over request. An MRM is derived from the functional safety principles of ISO 26262 (International Organization for Standardization, 2018) and is defined as the “system’s capability of transitioning the vehicle between [MRCs]” (Wood et al., 2019, p. 34). In contrast to the previously described taxonomies and regulations, this framework extends the definition of MRCs by adding take-overs from the vehicle operator and a limited operation mode as conditions. The standstill condition is represented by the MRC “End of Operation.” Therefore, this affects the transition process, allowing consecutive MRMs to achieve the final MRC (see Figure 1.5 and definitions in Table 1.2).

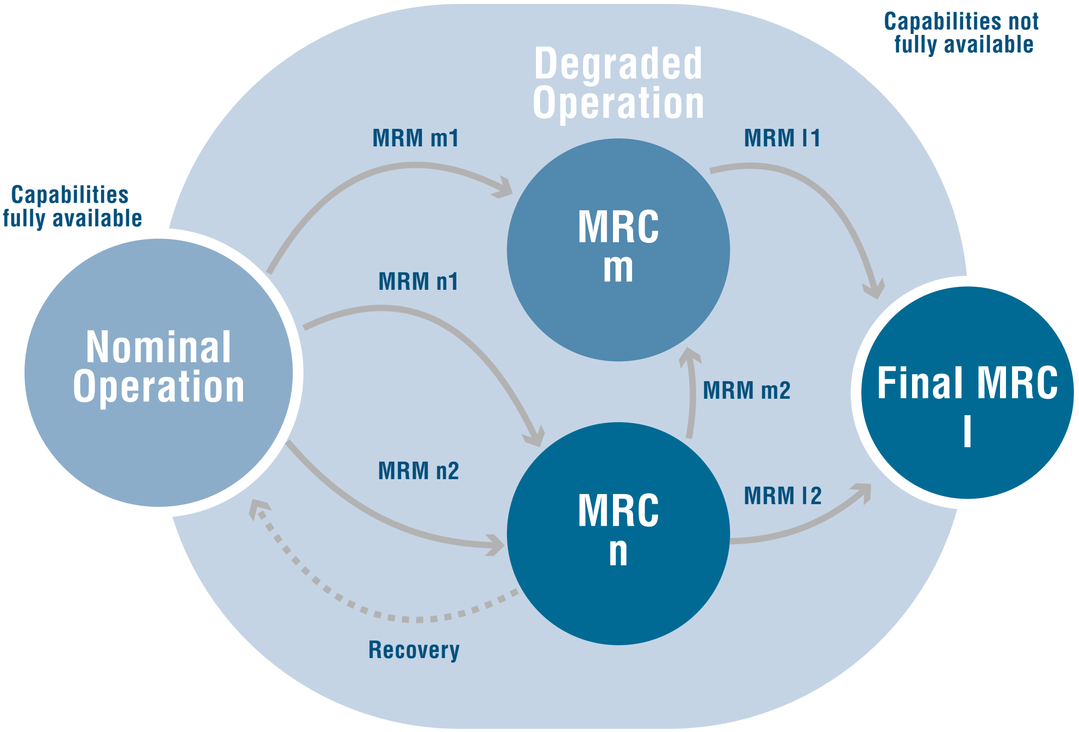

Figure 1.5: The interplay of MRMs and MRCs from Wood et al. (2019, p. 34).

Thirteen system capabilities, divided into fail-safe and fail-degraded, are proposed to fulfill all principles. One of the fail-degraded capabilities is the assurance of controllability for the vehicle operator which is, among other things, required for the “Vehicle-Initiated

Handover" principle. The description of the operator's control authority between MRCs lacks further elaboration in the document, leaving it contingent upon the automation level as per SAE J3016.

The white paper provides an example of the MRCs and MRMs of a Level 3 Highway Pilot that can drive up to 130 km/h. The three MRCs are a driver take-over (MRC 1), driving with a reduced speed of 80 km/h (MRC 2), and stopping in-lane (MRC 3). The proposed MRMs are issuing a take-over request to the driver (MRM 1), reducing the speed to 80 km/h (MRM 2) or until standstill (MRM 3) while continuing longitudinal and lateral control, and recovering to nominal operation (MRM 4).

Table 1.2: Definitions of MRMs and MRCs adapted from Wood et al. (2019, p. 35).

ID	Name	Definition	Target MRC
MRC 1	Take-over by the Vehicle Operator	The vehicle operator has completely taken over the driving task	
MRC 2	Limited Operation	Vehicle is still operational within reduced capabilities. There could be several limited operation conditions depending on the functional definition and remaining capabilities	
MRC 3	End of Operation	This condition describes a vehicle state that allows safe deactivation of the function	
MRM 1	Transition Demand	Request take-over by the vehicle operator	MRC 1
MRM 2	Limit Function State	Transition to limited operation. Depending on the MRC and the actual state, several MRM variants are possible	MRC 2
MRM 3	Comfort Stop	Comfortable transition to end of operation	MRC 3
MRM 4	Safe Stop	Due to severe failures, a fast but safe transition to end of operation is necessary	MRC 3
MRM 5	Emergency Stop	In case of sufficient rare severe system failures, an emergency stop is initiated to minimize risk, and so that the End of Operation condition can be reached	MRC 3
RECOVERY	Recovery	Limitations of capabilities are resolved and therefore nominal state is reached again	Nominal State

1.3 State of Research of Transitions

Transitions of AVs can be defined as periods between two different states (Flemisch et al., 2012) or levels in the case of SAE J3016. Lu and de Winter (2015) distinguish between driver and automation-initiated transitions, which are further divided into either the driver or the automation being in control afterward. For example, drivers may take over manual control due to preference or the recognition of automation failures (driver-initiated and driver in control). Drivers may also increase or decrease automation levels during the drive, e.g., by turning a lane-keeping assistance system on or off in addition to adaptive cruise control (driver-initiated and automation in control).

Concerning of MRMs, the previously described literature focuses on transitions that are automation-initiated and mainly terminated by a deactivation of the system followed by a manual drive. When considering MRMs, the control entity afterward can be both driver and automation, depending on the driver's reaction. Therefore, the transition definition of Lu and de Winter (2015) needs an adjustment for the concept of MRC achievement. Most of the research of automation-initiated transitions at Level 3 or higher focuses on a driver that is in control afterward, i.e., a phase starting with an RtI and a simultaneous deactivation of the system. This process was intensively researched throughout the previous years, which extent can be shown by the meta-analysis of 129 take-over studies by Zhang, Winter, Varotto, Happee, and Martens (2019). Different topics in the field of human factors were investigated, such as the modeling of take-over performance and the identification of influencing parameters by Gold (2016) and Radlmayr (2020). Petermeijer (2017) dedicated his research to interfaces and developed a vibrotactile seat to support drivers during the transition phase. Yang (2021) analyzed drivers' altered body postures due to NDRTs regarding their effect on the take-over performance and proposed countermeasures. Furthermore, Feldhütter (2021) and Jarosch (2020) investigated the effect of driver fatigue in driving simulator experiments and field studies on public roads using the Wizard-of-Oz approach. This transition process, the utilized evaluation metrics for driver performance, and the influencing factors will be described in the following even though the process differs when introducing MRMs (see Chapter 1.2). Nevertheless, results from these studies can be projected to some extent. This is because a driver take-over before MRM initiation is often preferred, thereby leaving the underlying problems unsolved.

The driver's role changes to a monitoring task with increasing automation levels. Consequently, it excludes the human from the control loop (Bubb, Bengler, Grünen, & Vollrath, 2015, p. 687). This entails known effects from the aviation sector that consist of two substantial issues and are summarized under the term "out-of-the-loop performance problem" (Endsley & Kiris, 1995). One of them is the loss of skills that accompanies the decrease in manual driving and, thus, a loss of training. Endsley and Kiris (1995) argue that skills are also required for detecting the need for manual performance, which is, for example, the detection of system-relevant failures without an RtI (SAE International, 2021, p. 31). The second one is the loss of situation awareness, which comprises three levels and is defined as 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"(Endsley, 1988, p. 97). The quality of one's situation awareness depends on individual factors, such as capabilities, experience, training, and workload (Endsley, 1988). Hence, perceiving the same information out of the environment (e.g., the vehicle in front slows down) may lead to a different comprehension (e.g., slow vehicle or traffic jam) and, thus, a different projection of the future state (e.g., adjust speed or hard braking combined with a warning of approaching vehicles). This effect applies among drivers (inter-individual) or even for the same driver at two points in time (intra-individual).

Feldhütter (2021) adjusted the transition process from Marberger et al. (2017) and Petermeijer, de Winter, and Bengler (2016). The latter included the work of Gold and Bengler (2014), Kerschbaum, Lorenz, and Bengler (2015), and Zeeb, Buchner, and Schrauf (2015). They all follow the principles of information processing by Wickens, Hollands, Banbury, and Parasuraman (2015) (Körber, Baseler, & Bengler, 2018). As shown in Figure 1.6, the take-over process starts with an RtI and ends with manual driving. Ideally, drivers shift their attention to the driving task and select and execute an action with adequate situation awareness. Therefore, triggering a salient RtI through multi-modal stimuli is recommended (Petermeijer, 2017; van Erp, Toet, & Janssen, 2015).

The transition phase consists of a mental and physical process that drivers go through simultaneously (Petermeijer et al., 2016). During the mental one, drivers shift their attention away from the NDRT by starting to look at the road again. This moment, called "Eyes-on road," happened on average after 0.69 s with a 5 s time budget in a study by Gold, Damböck, Lorenz, and Bengler (2013). With a 7 s time budget, Kerschbaum et al. (2015) reported 0.63 s, which was on average lower than the results from Gold et al. (2013) with 0.94 s. After cognitively processing the perceived information, drivers select their actions.

The physical process usually starts after the gaze reaction via posture repositioning. The first measurable moment in time here is the duration until drivers grab the steering wheel, which takes approximately 1.27 s (Kerschbaum et al., 2015). Similar results were found again by Gold et al. (2013) with 1.45 s (5 s time budget) and 1.79 s (7 s time budget). The next and most crucial moment in time during the physical process is the moment of action implementation or "Take-over time." This moment is labeled as the start of a clear driver intervention by Feldhütter (2021). Petermeijer et al. (2016) referred to the same moment but labeled it as a "Hands-on steering wheel" in their model. Gold et al. (2013) defined a conscious driver intervention as a steering angle change of 2° or brake input of more than 10%. As imposed by the UNECE (see Chapter 1.2), the steering threshold should also include a duration to become more suitable for detecting

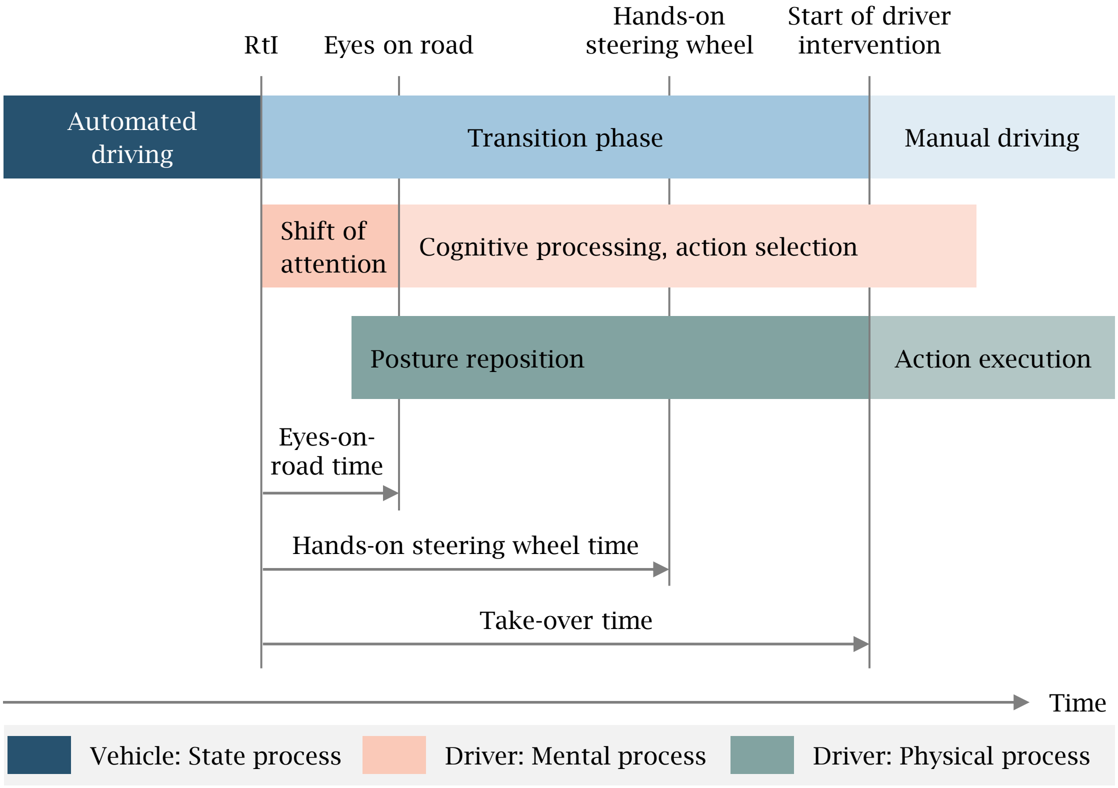

Figure 1.6: The schematic transition process from automated to manual driving adapted from Feldhütter (2021, p. 15).

interventions during MRMs. The mean take-over time in the meta-analysis was 2.72 s ($SD = 1.45$, $n = 520$) and ranged from 0.69 s to 19.79 s (Zhang et al., 2019, p. 291).

Take-overs can be assessed regarding their success by time and quality (Gold, 2016). In addition to the timing metrics listed so far (see also Figure 1.6), others are also reasonable regarding the research objectives and scenarios. For example, the gaze reaction time for designing salient stimuli (Gold, 2016), or the lane-change time when evasive maneuvers are required to resolve the situation (Yang, 2021). In terms of take-over quality, the longitudinal and lateral acceleration, the standard deviation of lateral position, the type of the first reaction, the time to collision (TTC), overshoots, and crashes are used for evaluation (Gold, 2016; Yang, 2021; Happee, Gold, Radlmayr, Hergeth, & Bengler, 2017). The enhanced time to collision (ETTC), as defined in ISO 15623, considers the accelerations of both vehicles and is more accurate for scenarios where the obstacle is not stationary (International Organization for Standardization, 2013).

The variance in the take-over times from the presented studies indicates that multiple factors may affect it. Zhang et al. (2019) point out that more time budget, inexperience in take-over situations, and a handheld device for an NDRT were associated with higher take-over times. Besides the latter, these factors could be confirmed in the studies from Gold (2016). Additionally, traffic density and age influenced the take-over performance. At the same time, drivers' workload, eyes-off-road time, and lane had only a minor impact. Radlmayr (2020) emphasizes that the take-over performance highly depends on the situation in which the transition process was evaluated.

These studies generally turned off automation at the beginning of the transition phase, and drivers were in total control and responsibility for vehicle guidance. This procedure has a major advantage for driver performance analysis since the input during this phase can clearly be differentiated and traced back to the responsible entity (Radlmayr, 2020). Therefore, including MRMs in this phase is a challenge for analysis. Additionally, driver performance can only be measured in case of a voluntary take-over, and the time and quality metrics are suitable to an extent. The utilized metrics within this thesis were accordingly adjusted and are given in Table 1.3.

Table 1.3: Metrics for evaluating transition phases with MRMs as used in this thesis.

Name	Description	Unit
Intervention	Decision to intervene (yes/no).	–
Intervention time	Time since the beginning of the transition phase until first driver intervention.	s
Manner of intervention	Performed maneuvers by drivers to resolve the situation.	–
Time to lane change	Time since the beginning of the transition phase until the ego vehicle enters the neighboring lane.	s
TTC or ETTC	(Enhanced) Time To Collision	[s]
Accelerations	Maximum longitudinal and lateral accelerations.	m/s^2
Longitudinal distance	The minimal longitudinal distance to the obstacle	m
Negative events	Accidents, overshoots, or interventions after the MRM started.	–
Trajectories	Trajectories during the transition phase or after achieving the MRC	–

In contrast to transition phases without MRMs, the first metric to analyze is the decision to intervene since the AV can automatically conduct an MRM, so drivers do not have to take over control. MRM malfunctions are not investigated in this thesis. If drivers intervene, the time and manner of intervention are analyzed. An intervention was defined analogically as a conscious driver intervention by Gold (2016) but with some adjustments.

One is that any accelerator or brake pedal input higher than 0% (rather than the 10% threshold) is recognized as an intervention. The driving simulator hardware used in this thesis did not send any signals if the participants put their feet on the pedals without pressing them. Therefore, the difference between applying conscious pedal pressure and repositioning the feet is covered. The other is adding a duration for steering input since the vehicle would automatically steer to achieve the MRC. Therefore, participants had to produce a 2° steering angle deviation for at least 1 s to be recognized as a different controlling entity. The manner of intervention, i.e., overtaking or standstill maneuvers, is assessed to evaluate the selected action concerning the situation. If participants choose to overtake, the time until entering the neighboring lane is measured. The resulting maximum accelerations during the whole transition process are analyzed by the following formula (Pacejka, 2005):

$$a_{res} = \sqrt{a_{longitudinal}^2 + a_{lateral}^2} \tag{1.1}$$

The most important metric to evaluate the success of the transition phases with MRMs in this thesis is the negative events that occurred. The first one is the frequency of accidents with any other traffic participants. Dangerous situations that could lead to an accident were covered with overshoots, low distances to the obstacle, and interventions timed after the start of an MRM. The latter is critical in case of opposed steering directions of the driver and the AV, leading to high vehicle dynamics. The TTC metric is chosen for scenarios with stationary leading vehicles. In contrast, ETTC was utilized for non-stationary obstacles, calculated with the following formulas (International Organization for Standardization, 2013):

$$TTC = \frac{\Delta s}{\Delta v} \tag{1.2}$$

$$ETTC = \frac{\left[-\Delta v - \sqrt{\Delta v^2 - 2 * \Delta a * \Delta s}\right]}{\Delta a} \tag{1.3}$$

The distance between both vehicles is labeled Δs, and differences between speed (v) and acceleration (a) are calculated as target vehicle minus subject vehicle.

For qualitative analysis, the trajectories of the ego vehicle during the transition phase and, more importantly, after achieving the MRC are analyzed to assess the process of traffic re-entering.

1.4 Risk

The term MRM automatically suggests that the maneuver will somehow reduce the collision risk to a certain level. It is important to note that it also inherits the term “Minimal” and not “Minimum.” A global minimum is unknown, especially prior to the maneuver. It depends on many factors that cannot be influenced and prognosticated with enough precision, e.g., surrounding traffic participants’ behavior. Wilde, Gerszke, and Paulozza (1998) point out that all human behavior is risky since no one can produce a desirable outcome with absolute certainty, and zero risk can only exist in its absence. Nevertheless, the goal of an MRM is to reduce the risk – but what is “risk”?

Risk can be classified into three areas according to Fuller (2005): objective risk, subjective risk estimate, and the feeling of risk. Before psychologists devoted themselves to this subject, mainly mathematicians and economists dealt with objective risk (Dornhöfer & Pannasch, 2000). Here, the main goal is to find an optimal decision in situations with an uncertain outcome. In road transportation, the objective risk may be defined as the accident probability and is often calculated post-hoc from accident data (Fuller, 2005). A driver’s estimate of the probability of an accident as an output of a cognitive process (subjective risk estimate) and the experienced feeling of risk towards the threat as an emotional response (feeling of risk) form the subjective areas of risk (Fuller, 2005).

An early goal of the research was to couple objective and subjective risks. One approach from Taylor (1964) was to measure the galvanic skin response as an indicator of driver arousal. Results showed a correlation between this metric and the accident probability in specific road segments. Even though the approach was later criticized and broadly discussed (see Fuller, 2005), it laid the foundation for further research. One of them is the risk homeostasis theory of Wilde (1982), in which drivers continuously strive to balance the perceived and target levels of risk. Thus, drivers will take actions to resolve the mismatch and those will lead to traffic accidents over a given time, i.e., the accident rate. In turn, this rate influences the perceived level of risk sooner or later and closes the control loop. The feeling of risk influences the subjective risk estimate in this model, according to Fuller (2005), which connects all three risk areas.

The zero-risk theory of Näätänen and Summala (1974) assumes that driver behavior is based on maintaining safety margins (Summala, 1988) and perceived risk has dichotomous properties, i.e., either perceived or not perceived (Plavšić, 2010). This model focuses on the motivating (excitatory) and warning (inhibitory) processes of driver behavior (Summala, 1988), which Fuller (2005) aggregates with the risk homeostasis theory of Wilde (1982) to the task-capability interface model. In contrast to the previous theories, the key variable for driver behavior here is the perceived task difficulty – and not risk.

This thesis tackles the objective risk during the transition phase with MRMs, which is defined as:

> Combination of the probability of occurrence of harm and the severity of that harm.
>
> — International Organization for Standardization (2018, p. 21)

Moreover, several approaches estimate the objective risk a priori to a situation, serving as an essential tool in the field of motion planning for AVs. Challenges arise due to the influence of numerous uncertainties, encompassing sensors (noise, range limitations, occlusion), perception (classification, localization), and prediction (intentions, trajectories) (Geisslinger, Karle, Betz, & Lienkamp, 2021). Quantifying risks is crucial for trajectory prediction, which especially helps to understand the underlying process of an MRM.

Risk assessment approaches are subdivided into two categories, i.e., deterministic and probabilistic (Noh & An, 2017). Deterministic approaches do not consider the previously mentioned uncertainties and use a rule-based estimation of the collision probability, which is also their main drawback. The advantages are simplicity and, consequently, computational efficiency. Probabilistic approaches are more intensively researched and include uncertainties while probabilistically describing the spatial and temporal relationships between the ego vehicle and other traffic participants. For this purpose, several methods can be found in literature, such as long short-term memory neural networks (Geisslinger, Poszler, Betz, Lütge, & Lienkamp, 2021), fuzzy logic (J. Schneider, Wilde, & Naab, 2008; Naranjo, Gonzalez, Garcia, & de Pedro, 2008), Bayesian networks (Noh & An, 2017; Schubert, Schulze, & Wanielik, 2010; Schubert & Wanielik, 2011; Schubert, 2012), and the Markov process (Ulbrich & Maurer, 2013; Althoff, Stursberg, & Buss, 2009). Some of these approaches consider risk metrics in the maneuver planning, such as the TTC or longitudinal distance. Two methods stood out in particular since they operationalize each risk component per definition – one in a deterministic (Glaser, Vanholme, Mammar, Gruyer, & Nouveliere, 2010) and one in a probabilistic manner (Geisslinger, Poszler, & Lienkamp, 2023) which will be briefly described in the following.

The chosen harm in both methods is a collision between the ego vehicle and other traffic participants. Therefore, the mathematical description of collision risk (R) is the product of the probability of a collision (P) and its severity (S) using the following equation:

$$R = P \times S \tag{1.4}$$

Both methods aim for a risk value between 0 and 1, which entails the same range for P and S. The deterministic approach of Glaser et al. (2010) uses the TTC and time inter-vehicular (TIV) as risk metrics and the corresponding collision probabilities (P_{TTC} and P_{TIV}) are linear relations between thresholds out of literature and regulations (see

Figure 1.7). The TIV is calculated similarly to TTC (see Equation 1.2). However, the relative distance is only divided by the ego vehicle's speed. Since two metrics are used in this approach to evaluate the total risk, both risk values (R_{TTC} and R_{TIV}) are summed up in the end.

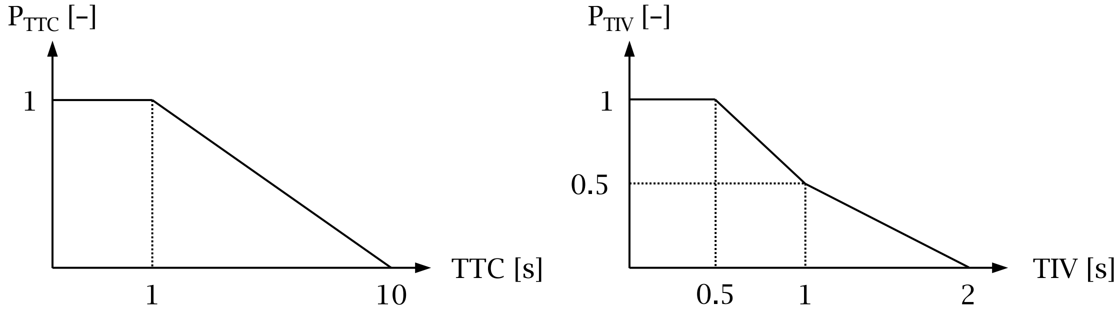

Figure 1.7: Collision probabilities due to TTC (P_{TTC}) and TIV (P_{TIV}) adapted from Glaser et al. (2010, p. 594).

Geisslinger et al. (2023) use their long short-term memory neural network to predict the behavior of traffic participants (see Geisslinger, Poszler, et al., 2021). They describe the model's output as "probability-based trajectory predictions as a bivariate normal distribution around a most-likely trajectory prediction" (Geisslinger et al., 2023, p. 142), shown in Figure 1.8. Consequently, a collision probability is calculated with the planned trajectory, but the calculation details are not explained further.

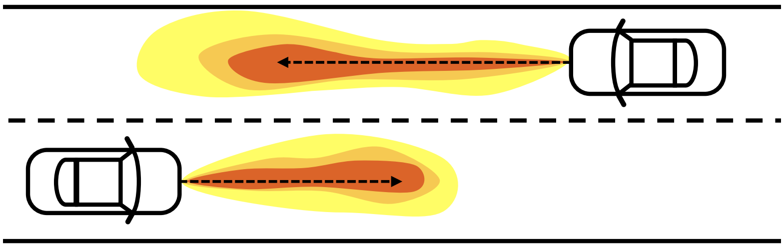

Figure 1.8: A schematic output of the probability-based trajectory prediction in one time step according to Geisslinger, Karle, et al. (2021).

The energy equivalent speed (EES) is utilized for the collision severity (S) in both methods but with differences in the calculation. It represents the change in vehicle velocity throughout the collision, wherefore it is also termed ΔV (Wang, 2022). With the help of the physical laws of conservation of momentum and (kinetic) energy, the EES is calculated by Glaser et al. (2010) as follows:

$$EES = \frac{2m_{obstacle}}{m_{ego} + m_{obstacle}}(v_{obstacle} - v_{ego}) \tag{1.5}$$

The vehicles' masses (m) and velocities before collision (v) are considered in the equation. Geisslinger et al. (2023) include the collision angle (α) and calculate it as follows[1]:

$$EES = \frac{m_{obstacle}}{m_{ego} + m_{obstacle}} \sqrt{v_{obstacle}^2 + v_{ego}^2 - 2 v_{obstacle} v_{ego} \cos \alpha} \tag{1.6}$$

The EES correlates with the injury that passengers receive during a collision and is measured by the maximum abbreviated injury scale (MAIS) score, ranging from a severity score of 1 (minor) to 6 (fatality) (Wang, 2022). The plus scores, i.e., MAIS1+, MAIS2+, and so on, represent the respective MAIS score and higher. Both methods use the MAIS+ curves to map the EES to a value between 0 and 1, while the deterministic approach refers to MAIS2+ and the probabilistic approach to MAIS3+ (see Figure 1.9). These curves are the output of the logistic regressions from all collisions, including frontal and rear-end collisions, and model the probability of passengers receiving a MAIS+ injury as a function of EES.

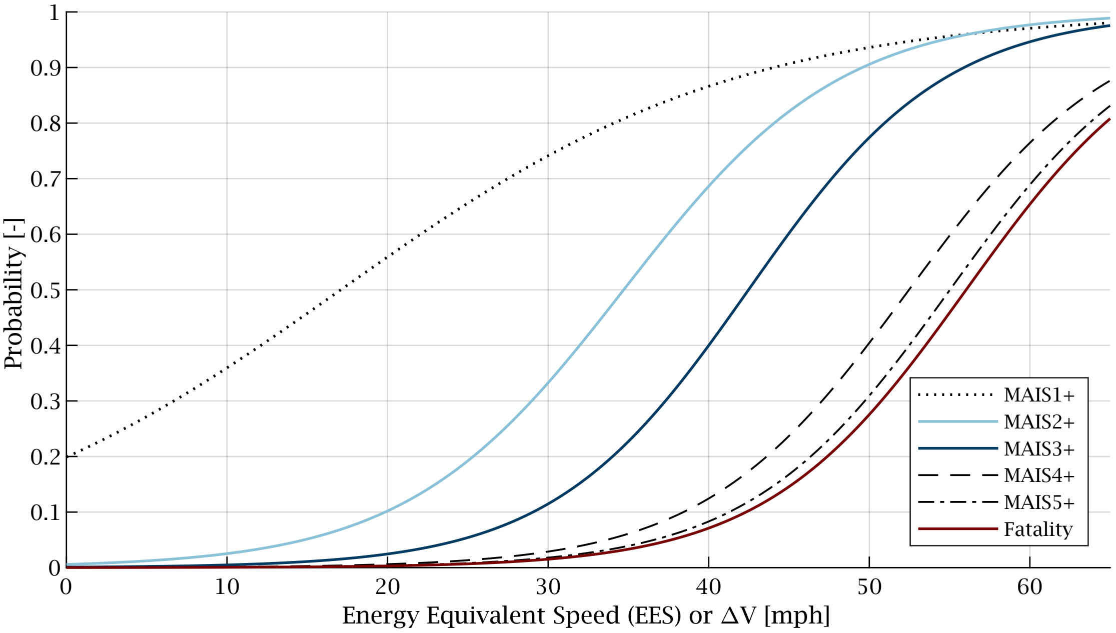

Figure 1.9: MAIS+ curves plotted from Wang (2022, p. 14).

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[1] Termed Δv_A in Geisslinger et al. (2023)

This thesis chose the approach to investigate the risk a posteriori because knowledge about driver behavior in transition phases with MRMs is required for a reliable estimation. For example, in extreme cases, assuming that the MRM is carried out without a collision and as planned by the system, the absence of driver interventions in MRMs would always lead to a safe standstill. Thus, the risk in the situations would always be equal to that estimated to select the maneuver, which would be low by design.

Therefore, negative events, such as accidents, overshoots, low (E)TTC values or distances, and interventions after the start of an MRM, are used to evaluate the severity of harm (see Table 1.3). The frequencies of these events will be measured, while an extrapolation to reality is not possible. For this purpose, there needs to be more knowledge about the failure probabilities of AVs and the occurrence probabilities of MRMs, which in turn depends on many external factors. Yet, the deployment of AVs with MRM functionality is still unknown. The goal is to reduce either the frequency of occurrence of the negative events, their severity, or both. Thereby, the approach corresponds to one of the principles of the International Organization for Standardization (2018): "[...] every order of magnitude in reducing the frequency of possible harm lowers the safety integrity level." (Wood et al., 2019, p. 35).

2 Scope of the Thesis

To conclude, an MRM is an automation system's function deployed whenever the planned trip cannot be continued and a transition to a lower automation level occurs (see Chapter 1.2). Ensuring MRM functionality in every situation, which can be described as a "generalization to unseen environments" (Janai et al., 2020, p. 225), is a demanding challenge for the AV's perception.

The challenge is likely why drivers will still play a fundamental role as it is currently proposed and regulated (see Chapter 1.2). Consequently, the known problems of driver performance degradation in transition phases may be replicated (see Chapter 1.3). The issues are intensified with MRMs due to the limited mental models of drivers compared to the broadly used automation levels, as researched by Homans, Radlmayr, and Bengler (2020). According to the authors, drivers mainly differentiate between three automation levels that correspond to multiple SAE levels: none to low automation (SAE Levels 0 and 1), medium automation (SAE Levels 2 and 3), and high to very high automation (SAE Levels 4 and 5). An MRM can be found at SAE Levels 3 and 4, which can simultaneously be assigned to two levels in the driver's mental model. Therefore, it is prone to confusion and makes it difficult for drivers to dissolve the responsibilities between them and the system, especially in transition phases.

The assumption at the beginning of this thesis was that introducing an MRM alone does not reduce the collision risk during a transition phase and that various factors must be considered. Hence, the research question is:

> Under what conditions does the collision risk decrease during
> a transition phase with MRMs when a driver is present?

Consequently, only safety-related aspects positively influencing collision risk are examined in this thesis. Other aspects, such as user comfort and trip efficiency, are not considered since MRMs are intended to fulfill the primary function of collision avoidance. Furthermore, this thesis aims not to apportion blame due to the expected differences between the developers and the human users but instead has the following goal:

> “Discovering the root causes of these differences is a necessary step toward informing the expectations of designers and managers so that operators are provided with automation that better meets their needs and are given the authority and decision-making tools required to use the automation to its best effect.
>
> — Parasuraman and Riley (1997, pp. 249 - 250)

Research in this area should be independent of current systems and changing regulations. Thus, no specific system is considered, for example, one according to an SAE level 3/4, an ALKS system according to UNECE, or similar. Instead, a transition phase with an MRM preceding an automated drive with NDRT is investigated. For the MRC to be achieved, the standstill of the ego vehicle is chosen, with which most of the literature agrees (see Chapter 1.2). The risk (see Chapter 1.4) should be reduced in this context. The following chapters, 3 - 6, are summaries of published articles, also attached in the appendix. Chapter 7 concludes the overall results, provides recommendations based on the investigated factors for designing transition phases with MRMs, discusses the limitations, and presents an outlook for future research.

At the beginning of the research, it was necessary to determine whether drivers would agree or disagree in principle with the MRM. A video survey in Chapter 3 investigates this topic under safe conditions. It provides an isolated observation of MRMs to judge if drivers' intentions contradict those of AVs. Based on the insights of this study, it was derived that drivers may intervene in an MRM. Consequently, as defined in Chapter 1.4, the risk would be most reduced by blocking the driver input during the transition phase. In Chapter 4, a dynamic driving simulator study is used to evaluate the influence of control authority, i.e., allowing or blocking driver input, contributing to the unsolved discussion by SAE (see Chapter 1.2). This study provides essential data for driver behavior and shows that further measures are necessary to reduce the risk. The goal is again to positively influence the risk by reducing the probability of intervention. One approach is to provide the driver with the necessary information to solve the situation. The required information is derived from literature analyses and the results of previous studies. The AV's human-machine interface (HMI) is the chosen medium for information transmission. Therefore, a contact analog head-up display (cHUD) is developed, evaluated by an expert review, and used for a driving simulator study in Chapter 5. In Chapter 6, one of the early questions related to MRMs has been addressed: Which maneuvers ensure the safety of the surrounding traffic? It is an important consideration, as an AV causing a standstill can become an obstacle for the surrounding traffic and may not offer a holistic solution to the problem. This study aimed to determine which MRMs are controllable for a manual driver from the perspective of a surrounding traffic participant. For this purpose, a new method was developed to evaluate controllability objectively.

3 **Article 1:** A Video Survey on Minimal Risk Maneuvers and Conditions

The literature research at the beginning of this thesis showed that an AV capable of automatically performing an MRM implies a higher automation level, e.g., according to SAE International (2021). Hence, it also implies that transition phases from a higher automation level to a lower one, i.e., from Level 3 to 0, are no longer challenging for the driver due to the AV's enhanced capability. Consequently, the known issues of transition phases are hoped to be solved. However, two conclusions could be drawn from the literature research: (1) a standstill in the vehicle's own, adjacent or, if existent, shoulder lane are desired MRCs and MRMs are the corresponding maneuvers; (2) drivers are still expected to take-over even though it is not mandatory. Different intentions between drivers and AVs were assumed based on the known driver behavior during transition phases without MRMs. Many factors must be defined before participants can practically experience MRMs, such as the permission of driver take-over, time budgets, and communication through the HMI. In order to determine them, possible underlying contradictions must be identified as a first step.

Forty-nine participants (26 male, 23 female) were invited to take part in the experiment and evaluated videos containing different MRMs on a laptop screen. Five scenarios were implemented in the driving simulator software SILAB 6.0, in which the ego vehicle is located in the left (three scenarios), middle (one scenario), or right lane (one scenario) of a three-lane highway. The longitudinal distances to other traffic participants varied for the scenario in the middle lane. The ego vehicle conducted the first possible three maneuvers, i.e., a standstill in the own lane and lane changes to the left and right, in each scenario except the one in the left lane. Here, only the lane change to the left was impossible, resulting in $(4 \times 3) + 2 = 14$ maneuvers. Due to the within-subjects design, participants experienced all maneuvers in a randomized order.

The results show that participants favor a lane change over a standstill maneuver and, if possible, one to the left lane over one to the right lane. Nevertheless, if they must choose, the desired MRC achieved in the long run was a standstill in the shoulder lane.

Since participants could only choose between standstill conditions in different lanes, they favored one in the shoulder lane over the others. The distance to other traffic participants in the scenarios had no significant influence on the dependent variables. Therefore, it either does not influence the drivers' decision for this method or at least not within the investigated range. In conclusion, the discrepancy between the drivers' preferred MRM and the literature's proposal was shown, and these contradicting intentions must be considered in future research.

Burak Karakaya	Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft preparation, Writing – review and editing, Visualization
Luis Kalb	Writing – review and editing
Klaus Bengler	Resources, Writing – review and editing, Supervision, Project administration, Funding acquisition

Karakaya, B., Kalb, L., & Bengler, K. (2020). A Video Survey on Minimal Risk Maneuvers and Conditions. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 64*(1), 1708–1712. doi: 10.1177/1071181320641415

4 **Article 2:** Investigation of Driver Behavior During Minimal Risk Maneuvers of Automated Vehicles

In transition phases with MRMs, no accidents would occur if error-free automation is implemented in the simulation. In this case, only the re-entering process into traffic after reaching a standstill would have to be investigated. With the findings from the previous study, it was possible to show an intention of drivers that contradicts the MRM, which can lead to interventions. Thus, the achievement of the MRC can no longer be ensured. Therefore, two questions arise: Do these different intentions lead to interventions? If so, is the risk reduced?

From a risk calculation perspective, the most effective risk reduction method is reducing the probability of the intervention occurring. This would mean allowing or blocking driver take-over in the transition phase. Therefore, a dynamic driving simulator study was conducted with a between-subjects design and the control authority as the independent variable. Input blocking was realized as cutting off the brake and accelerator pedal inputs but not the steering wheel to circumvent wrong information to the drivers, such as a malfunction of the AV. The steering wheel turned according to the MRM, and the automation did not turn off due to driver input but required high counterforces instead to change the vehicle's path. Fifty-six participants (39 male, 17 female) experienced two scenarios on a highway during the experimental drive, with the ego vehicle driving in the right lane and conducting an MRM to reach a standstill in the own or adjacent shoulder lane. The HMI was developed based on the previous study's results and concepts from the literature for this use case and consisted of visual and auditory messages. A short quiz was administered before the experimental drive to ensure participants understood the messages correctly. Incorrect answers were corrected, and participants experienced the HMI during the transition phase of the training drive.

An intervention rate of nearly two-thirds during one of the two MRMs could be found across both groups. Even the participants whose inputs were blocked accepted the high counterforces on the steering wheel to perform a different maneuver. If intervened, participants mainly chose to overtake the obstacle on the left. An overtake on the right, i.e., through the shoulder lane, only occurred two times. It can be concluded that the different intentions were the main reason for interventions, which is also reflected in the answers from the interview and the questionnaires. No statistically significant difference between the two scenarios nor the groups could be found in the analysis of the time of the first intervention. Participants intervened on average after the auditory and visual messages and during an MRM. During the overtaking maneuvers on the left, approaching traffic was not reliably detected by participants, leading to four accidents. Dangerous situations were also produced because of bad take-over quality. Furthermore, the total number of negative events was higher in the group with blocked input. In conclusion, the control authority did not reduce the risk as assumed. In the future, blocking must also be implemented to cut the steering wheel signals off, which can only be possible with drive-by-wire systems. For those who did not intervene, the majority of participants re-entered traffic from a standstill by overtaking the obstacle again on the left instead of using the shoulder lane to pass by. This strategy imposes a risky situation and must be considered when implementing MRMs.

Additional results

The following analyses of the data set from this study were performed but not included in the article. Since they are considered necessary for discussing the results at the end of this work, they are additionally reported here.

There is no significant relationship between the control authority, i.e., allowing or blocking driver input, and the decision to intervene in neither the scenario where the MRM aimed a standstill in the own lane, χ^2 (1, N = 56) = 0.65, p = .420, nor the shoulder lane, χ^2 (1, N = 56) = 0.66, p = .415. The average time of the first intervention of both groups combined happened after 6.02 s, 95% CI [5.48, 6.55].

Burak Karakaya	Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft preparation, Writing – review and editing, Visualization
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Karakaya, B., & Bengler, K. (2021). Investigation of Driver Behavior During Minimal Risk Maneuvers of Automated Vehicles. In N. L. Black, W. P. Neumann, & I. Noy (Eds.), *Proceedings of the 21st Congress of the International Ergonomics Association (IEA 2021)* (Vol. 221, pp. 691–700). Cham, Swiss: Springer International Publishing. doi: 10.1007/978-3-030-74608-7_84

5 **Article 3:** Minimal Risk Maneuvers of Automated Vehicles: Effects of a Contact Analog Head-Up Display Supporting Driver Decisions and Actions in Transition Phases

This study builds on the results of the previous one and considers the possibility that driver input blocking is not possible or legally allowed. Therefore, it aims to reduce the probability of harmful interventions occurring and thus positively influence the risk. The literature review revealed that the outcome of the driver's information process, i.e., the response execution, benefits from the HMI's previously provided and well-designed information. The cHUD, in particular, brings promising advantages already evaluated in other transition phases. Hence, this study aspired to find and evaluate a method to support the response selection and, thus, the response execution of drivers within the transition phase. Based on these findings, an HMI concept was developed and subjected to an expert evaluation in the first step. Six experts in interface design for automated driving assessed the concept using the checklist of Schömig et al. (2020). The recommendations were then adopted and implemented in the driving simulator.

Thirty-six participants (23 male, 13 female) took part in the static driving simulator experiment with a within-subjects design and the HMI as the independent variable. The AV triggered two transition phases within a drive on a three-lane highway with a shoulder lane while the ego vehicle travels in the right lane. The scenarios differed only in the presence of other traffic participants in the adjacent middle lane, i.e., either with or without traffic. The baseline HMI visually displayed the AV's planned MRM trajectory and marked the obstacle in the lane, while the experimental one additionally included recommended actions. The information in the instrument cluster and the acoustic messages were identical for both HMI concepts.

The results showed that over two-thirds of all participants intervened or voluntarily took over control in at least one of the scenarios independent of the HMI. In both scenarios, interventions were allowed so that a comparison with the study in Article 2 could be drawn. In the free scenario, the number of interventions was higher than in Article 2. In contrast, it was similar in the case of the occupied middle lane. Swerving to the left is again preferred, even if this lane is occupied. Nevertheless, the maneuvers performed in the event of intervention have changed for the better with the experimental HMI. Instead of swerving to the left, stopping on the hard shoulder or overtaking on the right occurred more frequently. Consequently, harmful interventions that lead to collisions and dangerous situations occurred with both HMI concepts. However, frequencies and proportions could be reduced with the experimental HMI.

Similar to the study in Article 2, interventions occurred after the acoustic messages of the HMI, but earlier, after approximately 4 s. Lane changes also tended to happen faster with the experimental HMI, i.e., 1 s difference in the free scenario. Additionally, transition phases with the experimental HMI resulted in a lower workload and positively influenced the trust in automation, as significant differences could be found. Re-entering into traffic after the standstill shows a similar picture as in the study in Article 2 and is risky: drivers overtake the obstacle at low speeds using the middle lane.

Additional results

The following analyses of the data set from this study were performed but not included in the article. Since they are considered necessary for discussing the results at the end of this work, they are additionally reported here.

The average time of the first intervention, combining the results with both HMI concepts, happened in the scenario with a free middle lane after 4.16 s, 95% CI [3.84, 4.48], and an occupied middle lane after 4.03 s, 95% CI [3.64, 4.41].

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Karakaya, B., & Bengler, K. (2023). Minimal Risk Maneuvers of Automated Vehicles: Effects of a Contact Analog Head-Up Display Supporting Driver Decisions and Actions in Transition Phases. *Safety, 9*(1), 7. doi: 10.3390/safety9010007

6 **Article 4:** Changing the Perspective: Assessing the Controllability of Minimal Risk Maneuvers for Surrounding Traffic Participants

The previous studies investigated transition phases with MRMs from the drivers' perspective. However, the literature research revealed that an AV could become an obstacle for surrounding traffic by achieving a standstill condition in its lane. A mixed traffic scenario consisting of manual and AVs is most likely becoming a reality in the early stages of AV introduction (see Chapter 1.1), in which drivers also must manually control the situation. Therefore, this study's research perspective was changed to solve the issue holistically.

A new method derived from the ISO 26262 (International Organization for Standardization, 2018) was developed to assess controllability objectively. Participants completed a benchmark drive after the familiarization drive and before the experimental drive. They had to solve an uncritical and critical situation. The collected driving performance data then spanned a scale for each participant, which later served as a reference in the experimental drive. Thirty-five participants (27 male, 8 female) took part in the experiment with a within-subjects design and the scenario as the independent variable. Participants sporadically encountered AVs in their driving that performed three different MRMs due to an obstacle in the roadway: a stop in their lane, on the adjacent shoulder, or a swerve to the left. The latter simulated an intervention by the occupant of the AV, which had been shown in previous studies to be an evasive maneuver to the left. Participants encountered AVs while driving behind them in the right and middle lanes. Together with the three MRMs, this resulted in $(3 \times 2) = 6$ scenarios.

The results show that the values obtained from the benchmark drive are well-suited for controllability assessment and could be further developed in terms of scenarios for future studies. Overall, drivers could better deal with the AV and its MRM in the lane next to it. In conclusion, the order from the most to the least controllable MRM remains consistent for participants driving in the middle and right lanes and is as follows:

1. Standstill maneuver in the shoulder lane
2. Evasive maneuver to the left (simulation of a driver intervention)
3. Standstill maneuver in the own lane

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Karakaya, B., & Bengler, K. (2023). Changing the Perspective: Assessing the Controllability of Minimal Risk Maneuvers for Surrounding Traffic Participants. In *2023 IEEE Intelligent Vehicles Symposium (IV)* (pp. 1–6). IEEE. doi: 10.1109/IV55152.2023.10186745

7 Discussion

In the course of the thesis, it has been presented how automation systems are defined and how their functions – and the MRM function in particular – are to be classified (see Chapter 1.2). The role of drivers in transition phases with and without MRMs and the challenges developers face in this context were elaborated (see Chapter 1.3). Risk metrics (see Chapter 1.4) were then used to conduct four studies (see Chapters 3 to 6) that systematically build on each other. Conditions under which the risk of a collision within the transition phase could be reduced were investigated. The findings of all studies are now brought together and discussed in this chapter (see Chapter 7.1). The previous model of the transition phase (see Chapter 1.3) is adapted according to the observed effects of the MRM function (see Chapter 7.2). Furthermore, the core of this thesis is the design of a transition phase based on the findings, which will be called the "Transition Protocol" in the following (see Chapter 7.3). Finally, this chapter lists the limitations of the studies (see Chapter 7.4).

7.1 Overall Results and Conclusions

Seven main conclusions were derived based on the results of the four articles in this thesis. They will be described within the limitations of the experiments in the following.

> **1** | There is a discrepancy between drivers' preferred MRMs and the AV's intended ones.

A standstill maneuver in one's lane, as suggested in the literature (see Chapter 1.2), does not correspond to the maneuver drivers expect from an MRM in a transition phase. This discrepancy was first demonstrated in the experiment in the video study in Chapter 3, where evasive maneuvers were preferred over a standstill in all scenarios. It also becomes apparent when looking at the maneuvers the drivers performed instead. Therefore, the scenario where the AV is in the right lane is considered to compare the results with the subsequent experiments. The percentage of drivers who chose to stand still in their lane was approximately 12% in the video study. In contrast, none of the participants in the two driving simulator experiments in Chapters 4 and 5 chose this maneuver. Stopping in the shoulder lane, as also suggested in the literature (see Chapter 1.2), was advocated by about 37% in the video study. However, in the driving simulator studies, this maneuver was performed by about 4% (see Chapter 4) and about 10% (see Chapter 5 and, for comparability, driving with the baseline HMI) of all participants. Eventually, the discrepancy could be shown. The video survey method was also suitable for this purpose, even though the number of maneuvers performed in the driving simulator studies was, as expected, lower.

2 | Drivers feel the urge to intervene in the transition phase to manually resolve the situation.

The AV could independently resolve the transition phase with an MRM in the driving simulator studies in Chapters 4 and 5, so driver intervention was not required. Therefore, among other factors, the decision to intervene was investigated in these studies. In the experiment in Chapter 4, no relationship was found between control authority, i.e., allowing or blocking driver interventions, and the decision to perform an intervention. Here, the number of interventions in at least one of the two MRMs the drivers experienced was about 64% in both groups combined. In the other experiment in Chapter 5, this number was about 73%, and the additional environmental information and the action recommendations communicated by the HMI to the driver did not influence the take-over decision either. The higher proportion resulted from significantly more drivers intervening in the scenario with a free middle lane than in the previous study. Furthermore, the interviews with the participants in both studies confirm that the previously described discrepancy mainly triggered the decision to intervene.

3 | Evasive maneuvers are favored by drivers over a standstill in the lane behind the obstacle. Further, one to the left is preferred over one to the right.

The fact that drivers prefer an evasive maneuver to come to a standstill in their lane behind the obstacle was already shown in the video study in Chapter 3. Here, it was also evident that they prefer to overtake obstacles on the left rather than swerve to the right and come to a standstill in the shoulder lane. The same result could be shown in the two driving simulator studies: 96% (see Chapter 4) and 100% (see Chapter 5) of all drivers decided to overtake on the left if the middle lane was free. However, if the middle lane was occupied and could not be used directly with a lane change, drivers still chose to do so by either gaining time through braking, thus opening up a gap, or doing a wrong gap assessment and causing a collision. Without additional environmental information and action recommendations, this proportion was 70% and could be reduced to 21% with appropriate communication via the HMI (see Chapter 5).

4 | Interventions may increase the collision risk and can be reduced with adequate countermeasures.

As the previous conclusions show, driver intervention is indispensable according to the current status. It leads to an overtaking maneuver in most cases without further driver support. Consequently, the negative events, as described in Table 1.3, will occur. In the case of an overtaking maneuver on the left, accidents could be observed primarily with road users approaching from behind (see Chapter 4) or already at the same height as the AV in the lane (see Chapter 5). The latter could have several reasons and cannot be inferred from the data since no eye-tracking data are available, and the participants were video-recorded from behind. According to a subjective assessment based on the videos, some participants caused a negative event despite moving their heads toward the side mirror. Therefore, a possible reason could be the "looked-but-failed-to-see" error known from accident research (White & Caird, 2010). Other dangerous situations when changing lanes to the left occurred when drivers kept the distance to the rear too small (both in terms of time and location), caused overshoots (unintentionally entering the next lane), or intervened after the MRM had started (partly coupled with the previous events). The latter was particularly problematic in the study in Chapter 4 because, although driver input was fully blocked except for the steering wheel, driver volition was greater. This led to accidents with other road users by drivers using high counterforce to steer the AV into the middle lane. In the case of an overtaking maneuver on the right, overshoots could also be observed, which consequently meant driving on the green area next to the hard shoulder and over delineators.

Overall, countermeasures could be tested and derived accordingly in this work. Blocking the intervention, considered the most effective measure initially, only applies under certain conditions (see the following conclusion). Providing the driver with additional situational and environmental information, e.g., blocked lanes, and corresponding action recommendations, effectively reduced the risk of a collision. For this purpose, a cHUD was used in the study in Chapter 5, but this is only one of many possibilities. In order to prevent an impulsive intervention in this phase, an additional approach would be to reduce the discrepancy described above with targeted driver training. The participants from this thesis were instructed before the experimental drive. Furthermore, this discrepancy even existed despite the possibility of testing the automation and a transition phase with an MRM beforehand. Other approaches would be to increase the experience with the automated system and transition phases with MRMs, which is also related to drivers' trust in AVs. Furthermore, pre-drive measures could be employed for driver compliance (e.g., Boos et al., 2021). However, the lack of a reaction also means the vehicle comes to a standstill in its lane or on the adjacent shoulder. This case was examined in the study in Chapter 6 and is challenging for surrounding traffic. For these reasons, several factors, significantly depending on the situation, must be considered for designing the transition phase with MRMs. These findings have been combined to derive a “Transition Protocol” that should be followed by the AV and will be discussed in more detail in Chapter 7.3.

The assumption at the beginning of this work was that the introduction of MRMs could easily repeat the known problems regarding the degradation of driving performance in transition phases. It was further assumed that the collision risk can only be reduced under certain conditions and appropriate countermeasures (see Chapter 2). Besides the results of this thesis, this assumption could be confirmed by the driving simulator study of Ichinose, Zhou, Saito, and Itoh (2022). They investigated the influence of information from an existing MRM function on driver behavior. However, the vehicle could not perform the MRM. If drivers would fail to take over, it would have resulted in a collision with the construction site, i.e., the system limit. The study aimed to measure driver behavior in the take-over situation, which was announced twice beforehand since it was a plannable system limit. Thus, the strategy was to let the driver take control, which every driver succeeded in doing within the 10 s time budget. Nevertheless, the take-overs were not without consequences, with the number of accidents being higher in the group aware of an MRM function of their AV. Three out of 14 participants (about 21%) collided with other vehicles while changing lanes or with the construction site. In the group where participants did not receive this information, it was one out of 14 participants (approximately 7%). Ichinose et al. (2022) justify the difference between the groups with a deficit in the mental and physical readiness of the drivers. Here, targeted measures, such as those investigated in this thesis, could help to support the drivers in their adoption and, thus, reduce the risk of collisions.

5 | The accelerator pedal, brake pedal, and steering wheel must be decoupled to prohibit driver intervention.

This conclusion may sound trivial, but as seen from the experiment in Chapter 4, non-compliance has safety-critical consequences. In this case, the steering wheel was not decoupled for technical reasons, so drivers applied high counterforces to change the path during the MRM. Combined with the inability to accelerate or brake, drivers have little chance of avoiding collisions. Decoupling the steering wheel so that no driver input is possible would require a steer-by-wire solution and is a technical challenge at the current state of the art (Mortazavizadeh, Ghaderi, Ebrahimi, & Hajian, 2020). Hence, this method should be employed as necessary or per requirements to ensure a guaranteed blocking of driver input. Turning off the input options at certain thresholds increases the driving dynamics in the transition phase and should be avoided. In the case of an MRM, it is advisable to take a different route (see Chapter 7.3) if blocking is impossible.

6 | From the perspective of surrounding manually driven traffic, an AV should not seek a standstill in its lane and, if possible, stop in the emergency lane or overtake on the left.

The controllability of MRMs was evaluated from the perspective of the surrounding traffic in Chapter 6. In this study, the AV, either immediately ahead or in a lane to the right of the ego vehicle, performed different maneuvers in which manually driving participants had to resolve the situation. The results show that stopping on the AV's hard shoulder is preferable. If this is impossible, the AV should swerve to the left into the middle lane. However, this is not a realistic MRM but corresponds to the maneuver drivers perform during their transition phase if they intervene to manually resolve the situation (see Chapters 4 and 5). Thus, this study simulated a driver's intervention and compared it to MRMs as they would be deployed according to the literature. Stopping the AV in its lane performed the worst and is therefore not recommended from this perspective. Finally, the options can be summarized as follows: 1) achieving AV standstill in the shoulder lane by blocking the driver inputs or implementing other driver-related measures, or 2) allowing drivers to intervene and providing assistance accordingly.

7 | Drivers need assistance for re-entering into traffic after coming to a standstill.

Reintegration into flowing traffic represents a safety-critical situation if the AV reaches a standstill condition. Thereby, it is regardless of whether the drivers achieve the state manually through intervention or automated through the MRM. In the studies in Chapters 4 and 5, it was observed that most drivers did not use the hard shoulder to pass the obstacle. Instead, lane changes to the left were made from a standstill, and the middle lane of the highway was traveled at low speeds. For this reason, drivers should also be assisted in this phase as part of the measures that intervene before or during the journey. Speaking in terms of the Principles of Operation of BASt (see also Chapter 1.2), the assistance during the journey should be deployed at the level of temporarily intervening functions (Principle of Operation C), and more precisely at α_I or higher.

7.2 Transition Phase Revisited

The transition phase from automated to manual driving, i.e., from at least SAE Level 3 to Level 0, and the ongoing processes were described in Chapter 1.3. Based on the findings in this thesis, the transition process was revised and adapted by the MRM function of the AV (see Figure 7.1). The process remains largely similar but primarily differs based on the driver's decision to take over within this phase. Therefore, the RtI was replaced by an announcement of maneuver (AoM), as driver take-over is not mandatory and had to be redesigned. In this work, the content of the AoM consisted of a signal tone and a computer-generated voice that announced the upcoming maneuver. In the instrument cluster, the maneuver was visually indicated accordingly. Additionally, in the HMI of the study in Chapter 5, the AV's planned trajectory was displayed in the cHUD. In both studies in Chapters 4 and 5, the acoustic announcements of the AoM lasted for about 3 s while the vehicle continued to drive automatically.

If the driver decides not to take over, the "Hands-on steering wheel" and, consequently, the "Action execution" steps can be omitted. In the case of a decision for the take-over, the action execution in the studies of this thesis took place either before the MRM started or during it. Hence, this was marked as an area in the process, and drivers continued manually after the end of the MRM at he latest. The average intervention occurred in the study in Chapter 4 after 6.02 s, 95% CI [5.48, 6.55], measured from the AoM. This value is 4.16 s, 95% CI [3.84, 4.48] with a free middle lane and 4.03 s, 95% CI [3.64, 4.41] with an occupied middle lane in the study in Chapter 5. Interestingly, in the latter study, the intervention was about 2 s faster, with drivers having about 3.5 s more time to take over (6.5 s total time budget). The adverse effect was found by Gold et al. (2013), where drivers reacted faster when less time budget for take-over was provided.

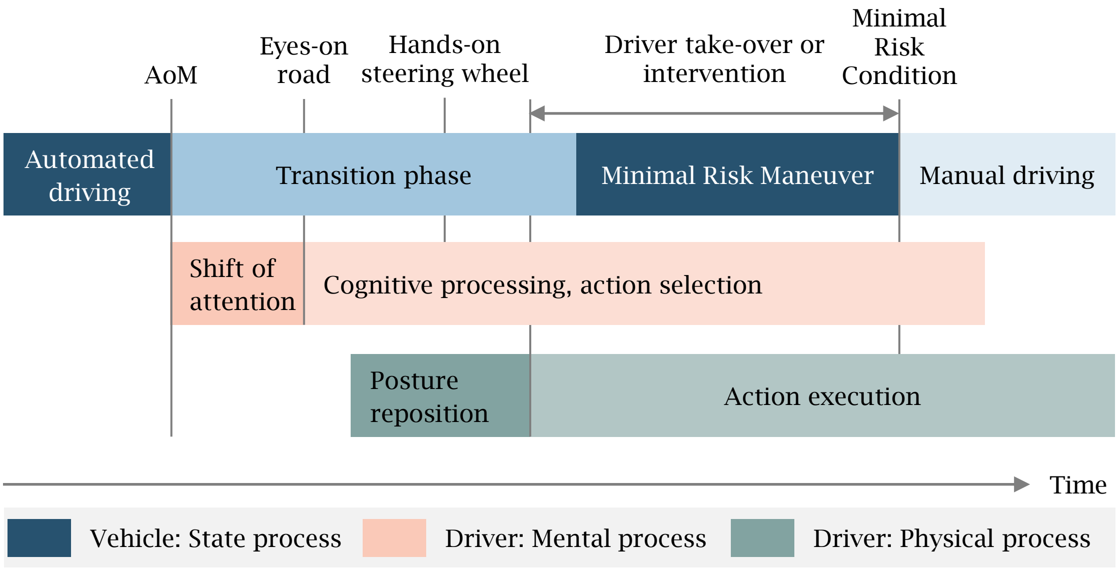

Figure 7.1: The revised transition process due to MRM functionality.

7.3 Practical Implication: Transition Protocol

Despite prior descriptions of the results and conclusions, the specific design for the transition phase with an MRM still needs to be answered. To ensure that the results are not confined to a research project, this work's objective is to facilitate the practical application of these findings within the automotive industry. Consequently, the "Transition Protocol" emerged from the studies (see Figure 7.2). In the form of a flowchart, it illustrates the process that the automated system should adhere to starting from the system limit. This process guides the system in executing an appropriate MRM based on the specific situation, the surrounding events, and conditions. The protocol is subject to certain boundary conditions, which are stated below. Any deviations from these conditions are discussed subsequently but were not included in the studies' investigations.

The first two boundary conditions were already stated at the beginning of the thesis (see Chapters 1.2 and 2) but are briefly repeated to understand the "Transition Protocol." First, it results from the premise of the automation system as a fallback solution that the vehicle can still perform the task of OEDR and thus detect both the system limit requiring an MRM and other environmental parameters. As can be seen from the system architectures, the waypoints and destination of an MRM are always calculated and use an independent perception (Popp et al., 2022). Even in the case of a perception failure, the last generated trajectory and other environmental information can be used (Ackermann & Winner, 2020). Finally, the "Transition Protocol" requires the following information: lane markings and their assignment (e.g., the hard shoulder is to the right of the AV), localization of the own vehicle (e.g., right lane), and objects in the own and neighboring lanes.

Condition 1: The environment and obstacle detection function operate at least until the transition phase begins, and the function's information can be used for that phase.

Second, a physical driver is in the AV since they continue to be assigned an essential role according to the current design of the transition phase (see Chapter 1.2). Additionally, the usual input options are available to them, i.e., a steering wheel, an accelerator pedal, and a brake pedal. Driver inputs must also be recognizable on the part of the AV to switch off the automation.

Condition 2: A physical driver is in the AV, and driver input can be detected during the transition phase so that, as a consequence, the automation can be switched off.

Third, the scenarios investigated took place on highways, with the AV driving in the right lane.

Condition 3: The transition occurs on highways or highway-like roads, such as dual carriageways, and the AV is in the right lane.

Fourth, the system limit under investigation that triggers a transition cannot be planned and, therefore, cannot prepare the driver for the phase over a more extended period. In addition, the cause does not allow continued journeys in the lane being traveled, for example, due to (1) non-identifiable objects, such as lost cargo or vehicle parts, (2) perceptual uncertainties, (3) unplanned road works or similar road works, (4) accidents, and (5) blue light operations.

Condition 4: The system limit cannot be planned, preventing the vehicle from continuing in the traveled lane.

The transition protocol from Figure 7.2 is described in the following using four main paths that can be traversed in this flowchart. As a reminder, the goal is to minimize the risk in the transition phase and not to reach a global minimum. According to the results of this thesis, two user groups need to be served: (1) users who want to intervene and act accordingly and (2) users who do not want to take over and let the MRM be performed. The main reasons for the latter are that they trust the automation, are overwhelmed by the situation, or are too distracted by the NDRT.

Path 1

System limit → [Free left lane] Yes → [Driver took over within 5 s] Yes → Disengage automation

The first question that runs through all paths and is decisive for the collision risk is that of a free lane to the left of the currently used one. It has been shown repeatedly in the case of a decision to take over that drivers want to swerve to the left and collide with vehicles in the lane. If this lane is free of other vehicles or the distance to them is large enough, the transition phase and the planned MRM should be communicated to the driver (AoM and planned trajectory). At the same time, a recommendation for action to the driver should be given. In this case, the recommendation would be to perform an evasive maneuver to the left while indicating that the lane is safe to drive. For this, the driver should be given a time window of at least 5 s since this corresponds approximately to the upper limit of the confidence interval for intervention times in Chapter 5. Although the time budget in the study was 6.5 s, this was not displayed. Drivers could have estimated it only from the projected trajectory. It is therefore assumed that the difference between the time budgets will not be perceived and that it can be shortened to 5 s in favor of technical feasibility. This recommendation is based on the results from the study in Chapter 5, in which all drivers intervened and overtook the obstacle on the left. The frequency of poorly executed interventions could be reduced thanks to the recommended action and the display of a free left lane. In addition, there are positive effects regarding workload and trust in the AV. If drivers intervene within the 5 s, the planned trajectory and the automation should be disengaged.

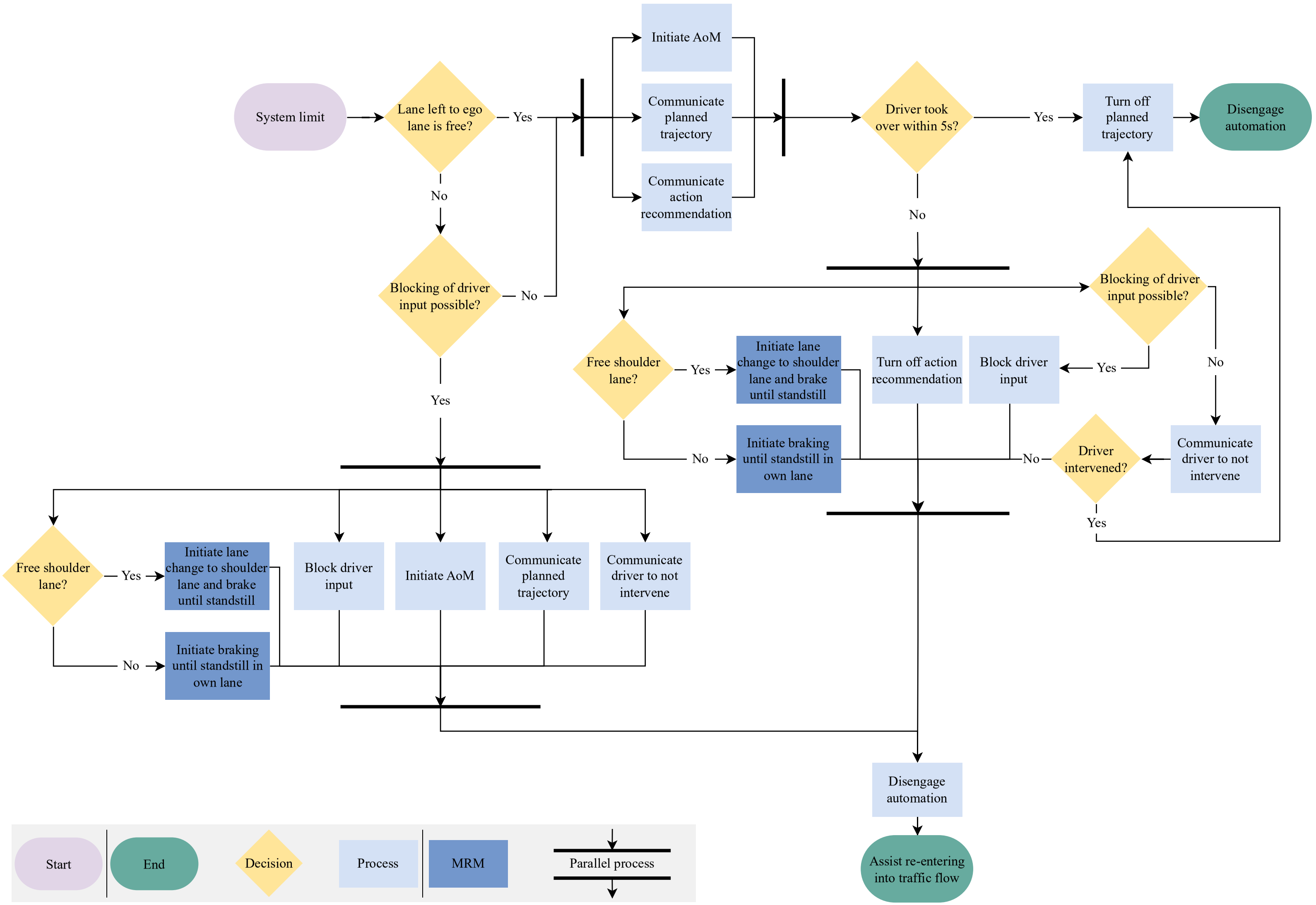

Figure 7.2: Transition protocol.

Path 2

System limit → [Free left lane] Yes → [Driver took over within 5 s] No → Disengage automation/Assist re-entering into traffic flow

If the driver does not take over the vehicle control within the first 5 s, no interventions should occur from now on, and the MRM should be initiated. Therefore, the recommended action from the previous step should be switched off simultaneously. If it is possible to block the driver inputs, then this would be recommended. This is because interventions during the MRM increase the driving dynamics and are an additional hurdle in dealing with the situation. In addition, it is more difficult for surrounding traffic to control (see Chapter 6). If this is impossible, the driver should be communicated to stop intervening, and in a more salient matter than in the studies of this thesis.

If the driver still does not intervene, an MRM should be selected depending on the shoulder lane: a standstill should be aimed for there if one is available and passable. If not, then the standstill should be in the AV's lane. The automation should switch off in the stationary state and assist the driver in re-entering the flowing traffic. This is because the results of this work showed (see Chapters 4 and 5) that drivers avoid overtaking the obstacle via the hard shoulder. However, the avoided maneuver represents a lower risk at low speeds than the favored alternative, i.e., overtaking the obstacle from a standing position on the left.

If, despite everything, the intervention takes place, the planned trajectory and the automation are switched off analogously to the first path.

Path 3

System limit → [Free left lane] No → [Input blocking possible] Yes → Assist re-entering into traffic flow

If the lane to the left of the current path is occupied and cannot be used immediately, the AV should no longer attempt a driver take-over. Since the primary driver take-over strategy is an evasive maneuver to the left, even in this case. This effect could be reduced but not eliminated in the study in Chapter 5 using the developed HMI. Therefore, the further course of the transition phase is dependent on whether the driver inputs can be blocked. A detailed recommendation on how to design the blocking can be taken from Conclusion 5 of Chapter 7.1. If blocking is possible, the AV should aim at stopping on the hard shoulder and only intend to stop in its lane if the hard shoulder is not available or passable. Although the latter is more difficult to control for surrounding traffic (see Chapter 6), collision avoidance is more crucial here. The upcoming should also be communicated (AoM and planned trajectory) to prevent drivers from misinterpreting the MRM and to keep the system consistent and transparent as in the other transition phases. Additionally, it is recommended to communicate to the drivers that interventions should not occur. The standstill can thus be reached with the help of blocking the driver inputs, and the automation can be switched off. From this point on, as previously described, it is necessary to assist drivers in re-entering into flowing traffic.

Path 4

System limit → [Free left lane] No → [Input blocking possible] No → Disengage automation/Assist re-entering into traffic flow

Suppose it is impossible to block driver inputs due to legal, ethical, or technical issues when implementing blocking as previously described (see Conclusion 5 in Chapter 7.1). In that case, the driver should at least be supported in this phase with an action recommendation and information about an occupied lane to minimize the risk. In the study in Chapter 5, this procedure reduced the probability of collisions and, among other things, encouraged drivers to stop on the hard shoulder. The further path is the same as the first path and will not be repeated.

The further course

The "Transition Protocol" outlines the processes the automation system should follow until the transition phase concludes. This phase ends with either the automation disengagement or the drivers' assistance in re-entering flowing traffic. Subsequently, the vehicle must re-evaluate the automation availability and communicate its state. The protocol comes into effect again at the next system limit, requiring an automation-initiated transition.

Deviations

Deviation from Condition 1: A functioning AV is an essential requirement for an MRM. In case of system failures, other maneuvers, such as the FMS (SAE International, 2021) or EM (UNECE, 2023a), come into effect. The goal of both is to reduce the kinetic energy as much as possible. Therefore, the usual aim is coming to a standstill, and driver intervention is undesirable. In addition, these phases are shorter, making driver intervention more difficult. Since these maneuvers were not part of the thesis and corresponded to other circumstances, they will not be discussed further.

Deviation from Condition 2: A deviation from this condition would mean that there would no longer be a physical driver in the AV, or at least the driver's input options would no longer exist. Accordingly, teleoperators would be responsible for vehicle control, and it would require too many resources to use them as a safe fallback level in a transition phase. Especially considering that it is very likely that one teleoperator will be responsible for multiple AVs, time-critical transitions would be challenging to manage. In this case, the MRM should always be deployed within the ODD without requiring a take-over request. Consequently, the new research question would be the safe reintegration into the flowing traffic after a standstill. Teleoperated vehicles in mixed traffic and at a speed of 80 km/h, the traveling speed at the beginning of the investigated transition phases in this thesis, are currently not a realistic use case to discuss further.

Deviation from Condition 3: First, the question would be how the AV should behave in a lane other than the right one on a highway or highway-like road. In these lanes, e.g., the middle or left of a three-lane road, stopping in one's lane would result in significantly higher differential speeds. A higher differential speed correlates directly with a higher collision severity (see Chapter 1.4), so stopping in these lanes should be avoided. Instead, the AV's strategy should include a higher time budget than in the "Transition Protocol" for a driver take-over and support the driver's action. If the AV can perform a safe lane change to the right lane and the trip still cannot be continued in an automated way, then the "Transition Protocol" can be executed.

On other roads and under other traffic conditions, driver behavior could change during the transition phase. In urban areas, abrupt stops occur more often, and drivers might be more compliant with the maneuver than on highways. In turn, this could reduce the rate of intervention. Overtaking on the right is also expected and could reduce overtakes on the left. Nonetheless, the number of interventions and overtakes on the left will likely be reduced but not eliminated. Therefore, it is advisable to support the driver in this phase. The "Transition Protocol" would be applicable here if there were at least two lanes and the vehicle was on the right. Since hard shoulders do not exist in urban areas, the MRM options would be reduced to a standstill maneuver in the lane.

However, one of the key challenges for an MRM is the timing aspect of the transition phase, as urban areas only sometimes allow for a long view regardless of sensor range. A time budget for a take-over and lower braking accelerations for an MRM (see Chapter 1.4) than for an EM/FMS would require longer-term planning by the AV. Thus, the introduction of MRMs in urban areas remains uncertain. Finally, the suggestion would be to trigger an EM/FMS due to the time criticality for unscheduled events and, if possible, to have a take-over phase beforehand. Feierle, Holderied, and Bengler (2020) investigated MRMs in urban environments and deliberately implemented the system with a short take-over phase of 0.7 s. The MRM was subsequently performed at a TTC of 0.9 s. The communication of the phase and the MRM were designed to be unobtrusive for this purpose, as driver intervention was not desired. With a comparatively high braking acceleration of 10 m/s^2, the maneuver would also be classifiable as an EM/FMS.

The results showed that participants did not intervene, thus reinforcing the proposed approach. The strategy for predictable system limits will be discussed in the deviation of the following boundary condition.

In the case of single-lane rural roads, the driver's behavior could be repeated since a standstill is also unusual here. Overtaking maneuvers on the left are more critical in this scenario due to oncoming traffic, which could occur less frequently but must be prevented. Hence, a more extensive time budget for taking over would be advantageous, accompanied by adequate support for drivers in their actions.

Deviation from Condition 4: In the case of predictable automation limits, such as road works, lane narrowing, or the end of ODD, the goal should be to prompt the driver to take over over a longer time horizon and thus avoid a standstill due to an MRM. Warning strategies that become more salient over time, such as warning cascades, are suitable for this purpose. In addition to visual, acoustic, and haptic warnings, vestibular ones could be transmitted to the driver with increasing urgency, such as a brake jerk. In the event of a failure to take over, the MRM should be performed while blocking the driver input.

In the study by Feierle et al. (2020), all participants took over at the latest at the second of three warning cascades so that an MRM could not occur. The warnings here consisted of visual and acoustic signals, the latter only from the second cascade onward. In the study by Ichinose et al. (2022), the system limit was also announced twice before the RtI, and the goal was to have drivers take over only from the RtI. Only one of the 30 participants did not comply with this and was excluded from the data analysis. It can be concluded that the salience and the character of the message, i.e., information or a request, are crucial for the take-over within the warning cascade. The challenge remains to achieve high take-over quality and, at the same time, high driver acceptance. The results of both studies confirm the proposed approach and would need to be validated in the future.

In addition, the AV could select lane sections with a hard shoulder or similar for the MRM since a standstill is preferred here. The system limit could be reached earlier than is theoretically possible, but this should be accepted to reduce the collision risk.

7.4 Limitations

A driving simulator was employed in all studies presented in this thesis. This choice is motivated by the unavailability of AVs equipped with an MRM function and the impracticality of conducting field studies due to potential risks for the occupants. These are two of the many known advantages of driving simulators, and others are the controllability, reproducibility, and realizability of novel concepts (de Winter, van Leeuwen, & Happee, 2012). The latter was particularly relevant to the study in Chapter 5, where an HMI concept could be implemented with comparatively little effort. A disadvantage of simulators and one of the most substantial limitations of the work is the limited physical, perceptual, and behavioral fidelity (de Winter et al., 2012). Thus, the hazard-free investigation also simultaneously leads to a difference in subjective risk, which is lower in simulations than in reality (S. A. E. Schneider, 2021). This could affect the number and type of interventions or take-overs in real-world driving. Most importantly, a difference in the reintegration process into flowing traffic may be expected, where participants in this thesis (see Chapters 4 and 5) overtook the obstacle on the left, even from a standing position. The motion platform of the driving simulator failed due to technical issues after the second study, affecting the mentioned limited fidelity. So, the study in Chapter 4 was dynamic, while the ones in 5 and 6 were static, although the same simulator was used.

The HMI concept in Chapter 5 was displayed using the simulation software for technical feasibility and worked flawlessly. Current displays would provide less space, and the contact analog placement of information would be worse. In this thesis, research was conducted to determine whether the presented information and action recommendations provided an advantage in the transition phase, with the HMI being just one of several mediums considered. Other means of delivery matching the technical capabilities need to be explored.

Scenario complexity depends on factors such as infrastructure, number and density of road users, time of day, and weather conditions. These factors were kept the same in the studies in this thesis. In this work, the complexity was intentionally designed low in order to study a best-case scenario in terms of AV: driving on a highway during daytime and sunny weather, triggering a transition phase in the right lane with existing hard shoulder and low traffic density (either no vehicles or a column of vehicles in the middle lane). However, studies showed that complexity affects reaction times, maneuvering behavior, and driver workload (Cantin, Lavallière, Simoneau, & Teasdale, 2009; Jurecki, 2019). Hence, the collision risk is expected to increase with complexity and needs to be researched.

Another notable limitation of this work is the participant collective, which only includes drivers with a valid driver's license from Germany. The results could differ when the experiments were repeated in other countries due to international differences in road traffic regulations. For example, drivers in Germany are only permitted to overtake on the right in cases of heavy traffic and congestion (BGBl, 2013). In contrast, some states in the U.S. allow it under additional conditions (California Code, 2011; Virginia Code, n.d.). This could have particular implications for the consent of MRMs on the hard shoulder and the overtaking strategy in the event of an intervention. The heterogeneous age and gender distribution could also affect driver behavior due to the predominantly male and young collective (mean age below 30 in all studies). For example, young drivers tend to engage in riskier driving behavior compared to older drivers and male drivers compared to female drivers (Rhodes & Pivik, 2011; Stephens, Nieuwesteeg, Page-Smith, & Fitzharris, 2017; Aluja, Balada, García, & García, 2023).

8 Outlook

Future research of transition phases involving MRMs hinges on their design, primarily focusing on the question: Will drivers continue to play an active role in the fallback level, and will MRMs be deployed only in the absence of a driver's response? In the context of private use of automated systems in mixed traffic, drivers will not be removed entirely from the system in the foreseeable future. Therefore, the results of this thesis should find a connection in taxonomies and regulations, such as SAE J3016, ISO 23793 (currently under development), and UNECE Regulation No. 157 (SAE International, 2021; International Organization for Standardization, n.d.; UNECE, 2023a). Thus, both the scientific community and system developers can be reached. Furthermore, the developed methodology for objective and individual controllability in Chapter 6 should find its way into ISO 26262 (International Organization for Standardization, 2018).

Based on my personal experience gained in the course of this thesis and from conversations with different stakeholders (participants, scientists at conferences, and project partners), I have found that the term "MRM" is vague. The disparity between the stakeholders was more remarkable than within their groups, reflecting a lack of a unified vision that led to differing expectations regarding the MRM function. For one thing, it is often used as a synonym for an EM/FMS, which could be because the literature does not distinguish them enough. For another, there is a notion that automation will defuse the situation regardless of its complexity with the maneuver and that the driver will no longer have a task. This could be mainly due to the term "Minimal Risk," which promises a minimum risk, even if not a global one. However, it is always about reducing the risk. Currently, the driver take-over at system boundaries represents the next lowest level, according to the literature. The next level after that is the MRM. It is advisable to rethink and adapt the term to mitigate the expectation at system boundaries. A suggestion would be, for example, the term "Risk Minimizing Maneuver" or, to define the driver's role even more clearly, "Driver Fallback Maneuver."

For further research in this area, alternative approaches to transmitting environmental information and action recommendations other than the variant of the cHUD in Chapter 5 should be investigated. On the one hand, it would be interesting to see whether the same information can be transmitted with less projection area or via other sensory channels. On the other hand, it should be investigated whether the same effects from this thesis can also be achieved via targeted driver training and education. Positive effects of driver training regarding the driving performance and the mental models of the drivers could already be found in studies with AVs of Level 2 and Level 3, which appeared particularly during the first interactions of the users with the systems (Ebnali, Hulme, Ebnali-Heidari, & Mazloumi, 2019; Ebnali, Lamb, Fathi, & Hulme, 2021; Forster, Hergeth, Naujoks, Krems, & Keinath, 2020).

The risk of an intervention was investigated a posteriori in this work, and the knowledge and data gained could be used for future research to estimate the risk of an intervention a priori. This would mean that the system assesses driver behavior before and the first time during an intervention to estimate whether it will increase or decrease the risk of collision. A method analogous to the trajectory planning of AVs (see Chapter 1.4) could be used for this purpose, although a probabilistic approach is desirable. Driver monitoring systems will be used in AVs (Dong, Hu, Uchimura, & Murayama, 2011; Khan & Lee, 2019) and may also find their use for this purpose. Specifically, driver gaze behavior could be included in the risk calculation before an intervention by verifying glances in the side mirrors, a shoulder glance before changing lanes, and observing the surroundings – all to enhance the first level of situation awareness along the way to rebuild it (Endsley, 1988). However, steering torque and brake pressure curves could also be used as metrics to identify driver intent and classify critical interventions in terms of driving dynamics and collision probability. Both metrics taken together may indicate the risk of driver take-over. This can be used during system-initiated transitions, for example, to justify blocking driver intervention before or during an MRM or for driver-initiated transitions during automated driving. As scenario complexity increases, a risk assessment becomes more important.

Ultimately, the introduction of AVs equipped with an MRM function should prioritize enhancing safety. In addition to addressing technical aspects of MRMs, it is essential to consider human factors, particularly in supporting and assisting driver decision-making during the transition phase. This consideration is especially important as users remain integral to the system and the fallback level. Furthermore, this thesis contributes to identifying the root causes of conflicts in this context between the automated system and the driver, intending to ensure that future users can experience AVs safely.

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Publications

A Video Survey on Minimal Risk Maneuvers and Conditions

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Known issues at higher automation levels are hoped to be solved by the systems capability to automatically perform maneuvers in order to achieve a so-called minimal risk condition. In this paper, we contribute to this developing research field and emphasize the driver's perspective. We have conducted a video survey with 49 participants showing different forms of maneuvers. The results show that drivers favor evasive maneuvers over coming to standstills and maneuvers to the left over right. However, the desired condition to be achieved is mainly the standstill on a shoulder lane. These conflicts should be considered for designing such systems and further investigated with different methodologies, such as driving simulators.

INTRODUCTION

Due to the introduction of automation in the automotive field known effects from the aviation sector such as loss of skill, higher workload, loss of situation awareness, etc. emerged again (Endsley, 1997; Thornton, Braun, Bowers, & Morgan, 1992). Much research has been devoted to this topic and researchers have studied these effects and their countermeasures so that drivers can benefit from an automated vehicle. A meta analysis of studies addressing higher levels of automation and their effects can be found in the publication by Zhang, Winter, Varotto, Happee, and Martens (2019). However, the problems occur as soon as the driver hands over the control and is allowed to be engaged in non-driving related tasks. According to the taxonomy of SAE this corresponds to level 3 and higher (SAE International, 2018). The effects can then be observed during and after the transfer of control back to the driver which usually marks the beginning of the transition process. For level 3 systems, this is introduced by the take-over request initiated from the Automated Vehicle (AV). From this point on, the driver is responsible for the performance and has to achieve a Minimal Risk Condition (MRC). The MRC is defined by the SAE International (2018) as follows:

> "*A condition to which a user or an ADS may bring a vehicle after performing the DDT fallback in order to reduce the risk of a crash when a given trip cannot or should not be completed.*"(SAE International, 2018, p. 11)

It is stated further that the AV at level 3 may automatically achieve a MRC in some circumstances but can not guarantee it in all cases. The main difference to level 4 systems is the AV being its own fallback level and possessing the ability to achieve this condition automatically under all circumstances within its operational design domain. A maneuver for that purpose is called Minimal Risk Maneuver (MRM). Regarding authority allocation, the taxonomy of SAE tolerates both solutions, i.e. allowing and preventing driver intervention. Similar approaches can be found at the Federal Highway Research Institute (BASt) (Gasser et al., 2012; Gasser, Frey, Seeck, & Auerswald, 2017), informal working group on ACSF by the UNECE (UNECE ACSF-24-05, 2019) and Safety First for Automated Driving (2019). All these groups believe that drivers can be attendant and interventions are possible, provided that is designed accordingly. But still the strategy is to start the MRM after escalating the warning and aiming a driver take-over in the first place. If this is not the case, the proposed MRCs are coming to a standstill on the own, adjacent or shoulder lane, if existent. The resulting MRMs are braking and/or steering to the slower lane in case it is (a) uncritical (UNECE ACSF-24-05, 2019), or (b) the risk of steering is lower than braking (Gasser et al., 2012). It is not further specified how the risk can be assessed.

Regardless of the system classification used and the transition design, as soon as the AV performs a MRM after a system boundary while a driver is behind the steering wheel, the known problems may not be solved. Moreover, disallowing driver input, especially in the ironic situation of a system boundary, would require an exact knowledge of a correct behavior which is to this state not possible with enough accuracy. Therefore, our research focuses on systems equipped with the capability of performing MRMs with an attendant driver. Our research question was: which minimal risk maneuvers and conditions are perceived as uncritical and are these corresponding to the proposed ones from literature? Therefore, a video survey has been conducted and presented in this paper.

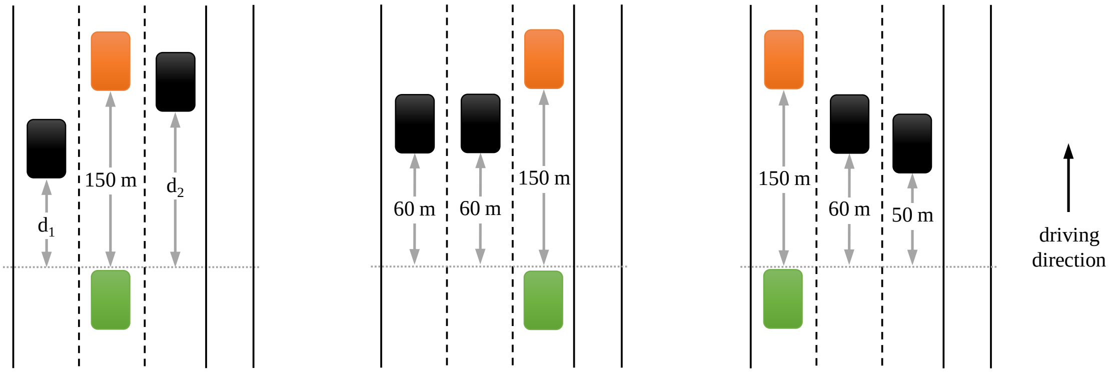
METHOD

Scenarios

In total, five scenarios were used for this study. All have in common that the obstacle causing the MRM, i.e. stranded vehicle with activated hazard lights, is located on the ego lane with a distance of 150 m (see Figure 1). Eight seconds prior to the start of a maneuver a simple double beep sound was used for announcement and to encourage participants watching the video carefully. Distances to surrounding traffic participants

Figure 1. Screenshot from the video right after the MRM "Standstill (ego lane)" in Scenario IV.

Scenario	d_1	d_2
I	30m	43m
II	30m	60m
III	60m	43m



Scenario I, II & III Scenario IV Scenario V

Figure 2. Sketches of the implemented scenarios. Ego vehicle is shown in *green*, the stationary obstacle causing the MRM in *orange* and other traffic participants in *black*.

can be retrieved from Figure 2. Vehicles behind the ego vehicle were not shown in the videos and therefore placed at distances greater than 70 m. The velocities of all vehicles including the ego one was fixed per lane, i.e. 80 km/h for right, 90 km/h for middle and 100 km/h for left lane. In this study, only the first maneuver that the automated vehicle could do was shown. For the Scenarios I to IV the MRMs were (a) maneuver to the left, (b) standstill on ego lane, (c) maneuver to the right. In Scenario IV the maneuver to the right was coupled with a standstill on the shoulder lane before reaching the stranded vehicle as this marks the end of a possible MRM. For the maneuver to the right and left, the velocity of the ego vehicle was constant and the video ended when the car completed the lane change. In Scenario V the two maneuvers were a standstill on ego lane and a maneuver to the right. For all standstill maneuvers the deceleration was approximately 0.8 g and parameters of longitudinal control were changed at 150 m before the stationary obstacle. However, the braking and pitch motion started at 85 m. The goal to achieve smooth maneuvers entailed the implemented distances and velocities.

Apparatus

After implementing the scenarios and the MRMs in the WIVW GmbH's software SILAB 6.0, a static driving simulator was used to display the front view of the vehicle. The rear mirror was placed on top of the screen (see Figure 1). The open-source software OBS Studio was used to record the screen with a resolution of 1920 x 1080 pixels. Questionnaires and the videos were displayed during data collection on a commercial laptop with a 15.6" screen and the same resolution as the videos.

Participants

The experiment had fifty-one participants and all fulfilled the requirements of possessing a valid driver's license and a minimum age of 18 years. Due to corrupted data, two participants were excluded from the study. The average age of the remaining forty-nine participants was 29.16 years (SD = 8.96) and ranged from 19 to 53 years. The sample consisted of 26 (53%) male and 23 (47%) female participants. Recruitment took place at the Technical University of Munich and local social environments.

Experimental design

This study used a within-subjects design with the scenario as the independent variable. Every participant experienced 14 maneuvers consisting of three per Scenarios I to IV and two per Scenario V. At the end of each scenario one video was shown as a short summary that contained all corresponding maneuvers. The order of scenarios was permuted while the maneuver sequence per scenario was unchanged. However, the sequence of maneuvers between the scenarios was permuted also. The sequence of the videos in the summary video followed the maneuver sequence as shown per scenario.

Dependent variables

After each video of a MRM the participants had to evaluate how risky the maneuver was. For that purpose, a five point scale from (1) not risky to (5) very risky was used. After all corresponding maneuvers to a scenario, a summary video was played and participants had to decide the overall safest maneuver (single choice). Additionally, the participants were asked to state a desired MRC per scenario that the system should achieve. Since standstill was the proposed condition from the literature, the four possible options were: standstill on the (a) left lane, (b) middle lane, (c) right lane, (d) shoulder lane. Statistical tests were carried out in IBM SPSS Statistics with a significance level of $\alpha = .05$. The data were analyzed using MATLAB (The MathWorks Inc.) and Excel (Microsoft Inc.).

Procedure

After welcoming the participant, information sheets about the experiment procedure, the purpose of the study and privacy statement were handed out requiring a signature on the consent form. The participant had to generate a code for pseudonymization on a separate sheet, which was not collected. The experiment started with an online questionnaire on the laptop where participants had to enter their code. At first, demographic questions were asked. Subsequently, the videos were shown and rated by the participants afterwards. As a concluding question, participants were asked if they would like to manually continue the drive after the presented first MRM or to let the automated system continue the journey.

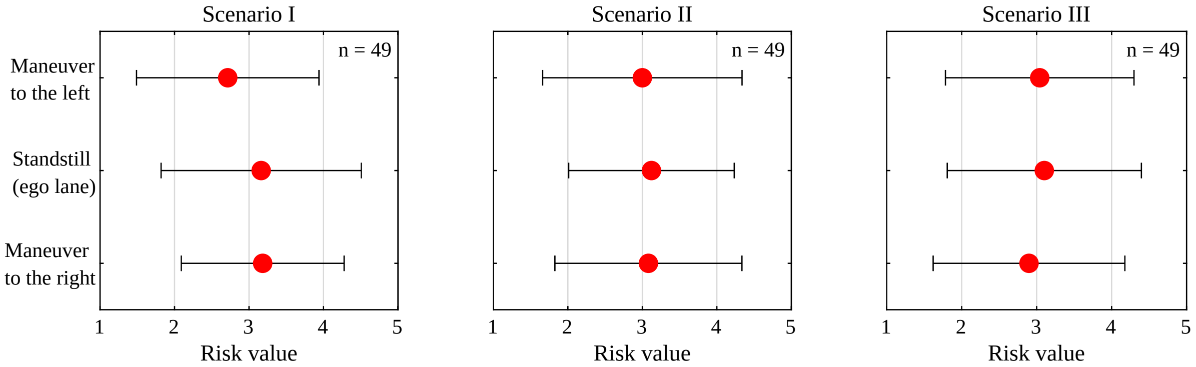


Figure 3. Risk assessment of each maneuver after watching the videos for the Scenarios I, II and III. Five point scale from (1) not risky to (5) very risky. Mean and SD values for each maneuver from top to bottom for *Scenario I:* 2.71 (1.22), 3.16 (1.34), 3.18 (1.09); *Scenario II:* 3.00 (1.34), 3.12 (1.11), 3.08 (1.26); *Scenario III:* 3.04 (1.26), 3.10 (1.29), 2.90 (1.28).

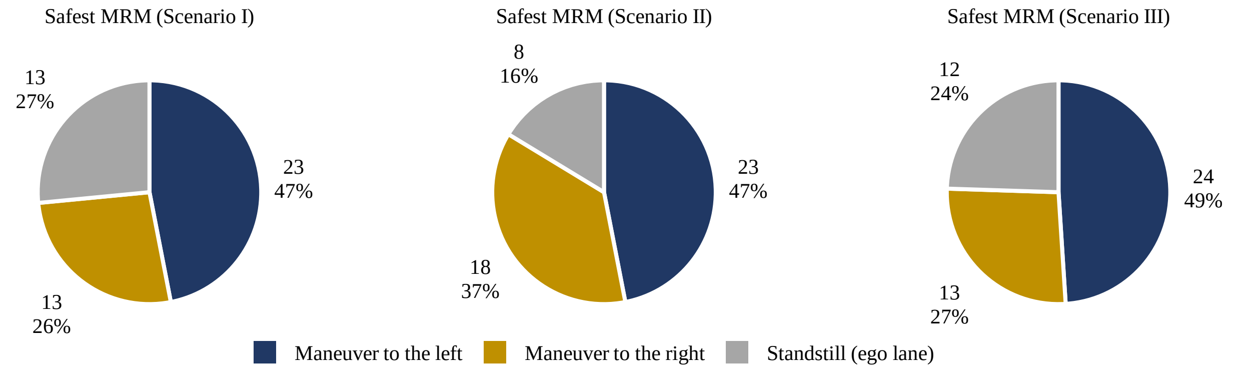


Figure 4. Distribution of the answers about the safest maneuver that was shown for the Scenarios I, II and III.

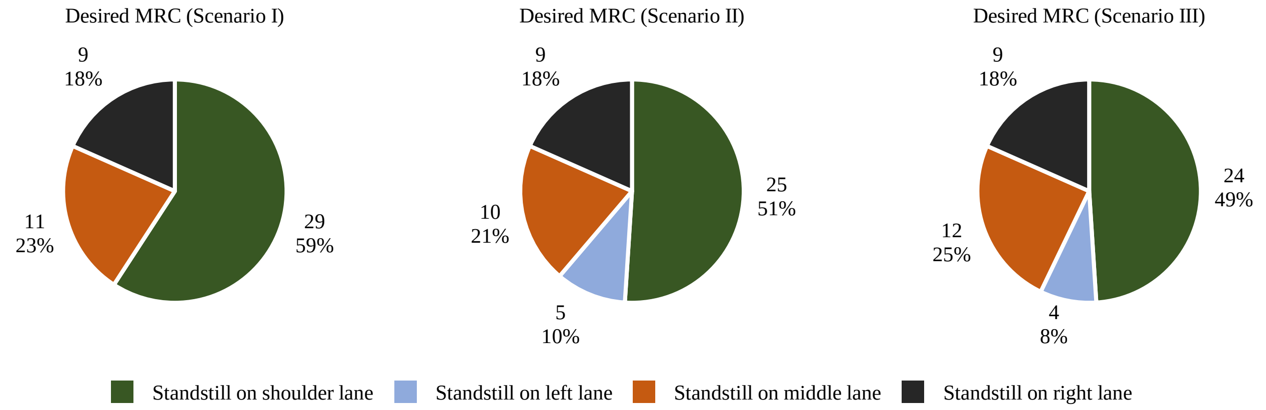


Figure 5. Distribution of the answers about the desired condition that should be achieved for the Scenarios I, II and III.

RESULTS

Scenario I, II and III

The Scenarios I, II and III only differed in the distances between the ego vehicle and the other traffic participants by the time the MRM was performed (see Figure 2). It was expected that this variation would have an impact on the risk assessment of the maneuvers, i.e. a less risky evaluation in case the distance was increased and vice versa. Also, there should be no differences for the evaluation of maneuvers with the same distance. As the results show (see Figure 3) the mean values for each maneuver within and between the scenarios fall around three (neutral position) with a high standard deviation. A Friedman test was carried out per maneuver using the Bonferroni correction to compare the risk assessment of a single maneuver between the scenarios and showed no significant results in each case (for the maneuver to the left: $\mathcal{X}^2(2) = 1.546$, $p > .999$; for standstill: $\mathcal{X}^2(2) = 0.173$, $p > .999$; for the maneuver to the right: $\mathcal{X}^2(2) = 1.389$, $p > .999$).

The overall evaluation of the safest maneuver after seeing all videos per scenario showed that the majority chose the maneuver to the left followed by the maneuver to the right and

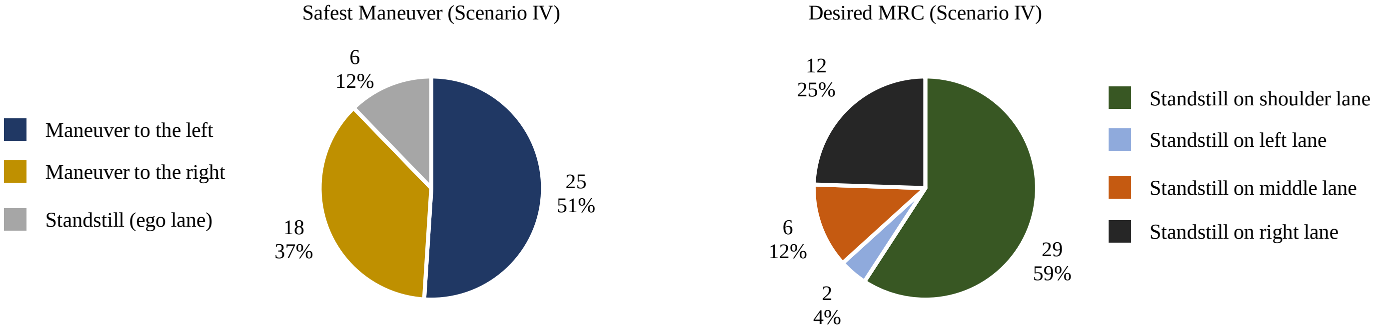


Figure 6. Safest MRM and MRC rated by the participants after Scenario IV.

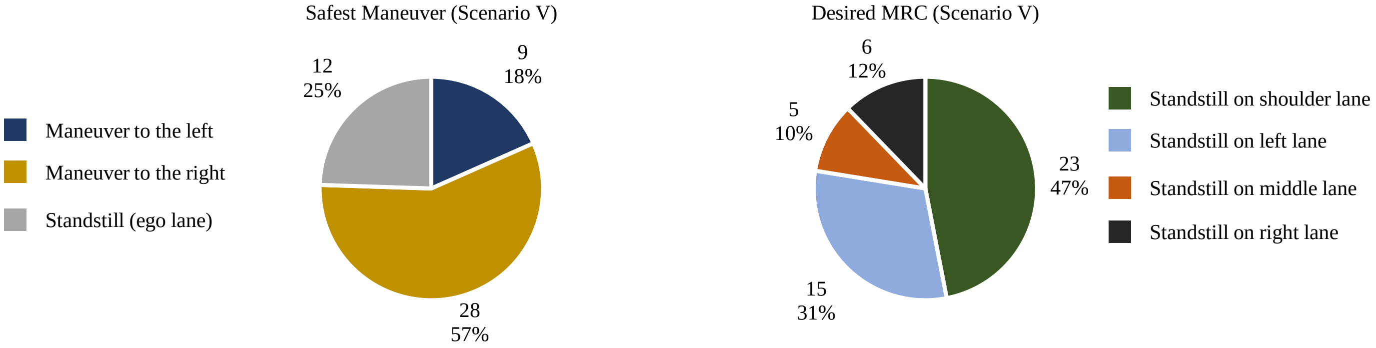


Figure 7. Safest MRM and MRC rated by the participants after Scenario V.

standstill on ego lane (see Figure 4). In order to compare the decisions between the scenarios, a Cochran's Q test with Bonferroni correction was conducted and showed no significant results for each maneuver (for the maneuver to the left: $\mathcal{X}^2(2) = 0.118$, $p > .999$; for standstill: $\mathcal{X}^2(2) = 4.200$, $p = .366$; for the maneuver to the right: $\mathcal{X}^2(2) = 2.941$, $p = .690$).

Furthermore, standstill on the shoulder lane was the preferred MRC by most participants in all three scenarios followed by the standstill on the middle, right and left lane (see Figure 5). Again, differences between the scenarios were analyzed with a Cochran's Q test using the Bonferroni correction. It showed no significant differences for all four conditions between the scenarios (for standstill on the shoulder lane: $\mathcal{X}^2(2) = 4.667$, $p = .291$; left lane: $\mathcal{X}^2(2) = 6.000$, $p = .200$; middle lane: $\mathcal{X}^2(2) = 0.400$, $p > .999$; right lane: $\mathcal{X}^2(2) = 0.000$, $p > .999$)

In Scenarios II and III, 10% and 8% of the participants stated that the automated system should achieve the MRC of a standstill on the left lane, which is the fastest lane. This result was not expected due to this being an unusual activity for any vehicle, either one with a driver or an automated vehicle.

Scenario IV

The associated risk levels for each maneuver in Scenario IV has again a high SD and a mean close to the neutral position (see Figure 8). Due to lower mean and SD values of the maneuver to the left, a tendency of a comparably lower assessment can be stated.

The maneuver to the left was chosen as the overall safest maneuver (51%) followed by the maneuver to the right (37%) and standstill on ego lane (12%). The desired condition to be achieved by the automated system was mainly the standstill on shoulder lane chosen by 59% of the participants, whereas the standstill on ego lane was chosen by 25% (see Figure 6).

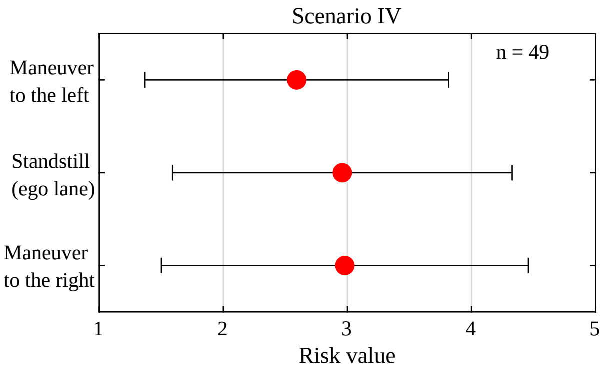


Figure 8. Risk assessment of each maneuver after watching the videos for the Scenario IV. Five point scale from (1) not risky to (5) very risky. Mean and SD values for each maneuver from top to bottom: 2.59 (1.22), 2.96 (1.37), 2.98 (1.48).

However, some unexpected results were the desire of some participants to come to a standstill on the middle (12%) and on the left lane (2%). In both cases, this means one or two maneuvers to the left and coming to a standstill.

Scenario V

As the results in Figure 9 show, the risk assessment for the maneuver standstill has a tendency to be higher than the maneuver to the right due to a higher mean with a comparable SD.

The safest maneuver, chosen by 57% of the participants, was the maneuver to the right lane, followed by the standstill on ego lane (25%) and maneuvering to the left (18%) (see Figure 7). In this scenario, a maneuver to the left was not shown in the videos since the ego vehicle was on the furthermost left lane. However, some participants stated this maneuver to be the safest. One possible explanation could be that the vehicle should use the space between the guardrail and the obstacle for the maneuver and they rated this fictional maneuver as the safest.

Coming to a standstill on the shoulder lane was the preferred condition that the automated system should achieve for 47% of all participants. The standstill on the ego lane represented by the answer "Standstill on left lane" was chosen by 31%. Again, here the desired MRC of coming to a standstill on the middle lane or on the right lane while a shoulder lane is existing was unexpected (see Figure 7).

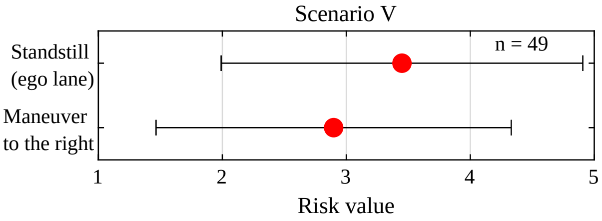


Figure 9. Risk assessment of each maneuver after watching the videos for the Scenario V. Five point scale from (1) not risky to (5) very risky. Mean and SD values for each maneuver from top to bottom: 3.45 (1.46), 2.90 (1.43).

Continuation of automated driving after a MRM

Lastly, the participants were asked if they would like the automated system to continue the journey after the first MRM was performed provided that the system was operational. In total, 21 participants (43%) voted for yes and 28 participants (57%) would like to take over the control and continue driving manually.

DISCUSSION

According to the risk assessment of the Scenarios I to III, no clear conclusions can be drawn within a scenario. The evaluation of the safest MRM shows a distinct preference for the maneuver to the left. However, the desired MRC that most of the participants want to achieve was the standstill on shoulder lane, leading to a contradictory statement. A possible reason for this is that that multiple MRMs are accepted by drivers as it is also proposed by Safety First for Automated Driving (2019), where the transition process is modeled as a state machine. But nearly half of the participants stated to overtake the control after the first MRM which could endanger achieving the intended MRC. The variation of distances to other traffic participants showed no influence on any of the dependent variables deducing that either the distance has no influence on the risk perception for this method or other distances should be investigated.

In Scenario IV, the risk assessment shows a tendency of lower associated risk values for the maneuver to the left which is in accordance with the overall rating of the safest maneuver. Again, here the standstill on the shoulder lane is the preferred condition that should be achieved by the system. It is surprising that for this best-case scenario for transitions with MRMs from a developer perspective especially, the results again show the discrepancies in the rating of the safest maneuver versus the desired MRC.

The tendency of lower risk values for maneuvering to the right could be affirmed in the answers for the safest MRM in Scenario V too. Still, the most desired MRC was coming to a standstill on the shoulder lane.

Limitations

The maneuver to the right was not exactly as smooth as to the left. Participants were told to not consider this in their evaluation. In order to randomize the video sequence, the questionnaire always included the same questions which could lead to confusion and be the reason of the unexpected results in Scenarios IV and V. For future studies, it is definitely recommended to investigate this topic further in driving simulator studies and consider the presented results when designing MRMs.

Conclusion

In conclusion, our results indicate that drivers tend to assess an evasive MRM less critically than coming to a standstill regardless of the situation and furthermore prefer left over right. However, the condition that they would desire from an automated vehicle to be achieved is mainly a standstill on the shoulder lane. Therefore, this inconsistency is crucial for designing AVs with the ability to perform MRMs.

ACKNOWLEDGMENT

This research was conducted within the project "CAD-JapanGermany: HF" which is funded by the Federal Ministry of Education and Research of Germany. We would like to acknowledge Emel Yildiz for her assistance in data collection.

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Investigation of Driver Behavior During Minimal Risk Maneuvers of Automated Vehicles

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Abstract. Minimal Risk Maneuvers (MRMs) are introduced to reduce the risk of an accident during the transition from automated to manual driving. In this paper, we present the results of a dynamic driving simulator study with 56 participants with the control authority as the independent variable, i.e. allowing and blocking driver input during the MRM. In order to not communicate wrong information, input blocking was established by disabling the brake and gas pedal but not the steering wheel. The latter turned according to the performed MRM and participants had to overcome high counterforces to change the vehicle's direction. Two scenarios on a highway were investigated with the ego vehicle located in the right lane and only differing in the implemented MRM, i.e. stopping in the own lane or maneuvering to the shoulder lane combined with a standstill. Our results show a high intervention rate in both groups. Participants intervened mainly by maneuvering into the middle lane and after the Human-Machine-Interface announced the upcoming maneuver. In total, four accidents and five dangerous situations occurred due to interventions in both groups. Trajectories during re-entering into traffic showed that participants favored the middle lane over the shoulder lane here as well. To conclude, allowing or blocking driver intervention did not reduce the risk of an accident and more countermeasures need to be taken.

Keyword: Minimal Risk Maneuver · MRM · Level 4 · Driver behavior

1 Introduction

Minimal Risk Maneuvers (MRMs) are part of the functionalities of vehicles at higher levels of automation that correspond to level 3 and higher according to the SAE taxonomy [1]. Whenever these automated vehicles reach their boundaries, MRMs are employed to reach a Minimal Risk Condition (MRC) to reduce the risk of an accident. The requirement for these maneuvers is that the automated system is still functional, otherwise a failure mitigation strategy would take place. For level 3 systems, the driver is mainly responsible to achieve an MRC and the system could execute MRMs only in some circumstances. This is opposed to level 4 systems, in which the automated system itself is responsible for this in every situation. Nevertheless, the literature [1–4] still leaves some questions unanswered by stating that MRMs could start either after requesting the driver to take-over control or immediately. Furthermore, it is still under discussion if intervening in these automated maneuvers should be allowed or not. Since these aspects

N. L. Black et al. (Eds.): IEA 2021, LNNS 221, pp. 691–700, 2021.
https://doi.org/10.1007/978-3-030-74608-7_84

are not regulated by law, different interpretations and implementations are possible. As an example, Honda announced together with their receipt of a type designation for level 3 automated driving, that an MRM is a key safety standard for their vehicles. In this case, the automated system must safely stop the vehicle whenever a transition of control cannot be made [5].

Karakaya et al. [6] showed the discrepancy between the literature's versus the driver's idea of an MRM, i.e. stopping the ego vehicle in-lane or on the shoulder lane versus overtaking from the left. These findings were considered for the design of a Human-Machine-Interface (HMI). From a risk assessment point of view, the risk during a transition phase with MRMs is the occurrence of an accident times its probability. This risk in turn is apparent if either the MRM has malfunctions, or if the driver can intervene intermediately. Hence, we conducted a driving simulator study to contribute to the discussion about the design of transition phases with MRMs with the research question: does the discrepancy between the driver's and literature's perspective of an MRM [6] lead to interventions if input is allowed or blocked – and if there is an intervention, is the risk still reduced?

2 Method

2.1 Scenarios

In total, two scenarios were used for the transition phase of the 25 min-long experimental drive. Both had in common that the ego vehicle is driving at 80 km/h in the right lane of a three-lane highway with a shoulder lane and right-hand drive. The obstacle causing the MRM, i.e. a stranded vehicle with activated hazard lights, was in the same lane as the ego vehicle at a distance of 200 m. That corresponds to a TTC of 9 s at the time the upcoming MRM was announced, later referred as the Announcement of Maneuver (AoM). The MRM itself was performed by the system after the AoM was finished. The two scenarios differed only in the performed MRM by the system, i.e. a standstill maneuver in the own lane ("MRM stop") and an evasive maneuver to the right combined with a full stop in the shoulder lane ("MRM evasive"). Since the vehicle came to a standstill after both maneuvers and marked the end of an MRM, the drivers were told to continue driving manually and therefore had to re-enter into traffic. After a short period of time, automation was available again and the participants were instructed to activate it. An uncritical scenario was implemented for the training drive, where participants were driving in the middle lane with no obstacle or other traffic participants. To familiarize themselves, the "MRM stop" was triggered and led to a full stop in the own lane.

2.2 Apparatus

The study was conducted on a modular dynamic driving simulator with a 120° horizontal field of view provided by three 55-in. screens with Ultra HD resolution. A rear mirror is integrated into the front view of the middle screen, while side mirrors are in two additional displays. An additional display located behind the steering wheel was used as a freely programmable instrument cluster (IC). Driving simulation was implemented via SILAB 6.0 from the Würzburg Institute of Traffic Sciences. For video recording of the experimental drive, a GoPro HERO 4 Silver Edition was mounted on a tripod and positioned behind the driver. A Sony Xperia Z Ultra was used for the non-driving related task during the automated drive, i.e. the Surrogate Reference Task (SuRT).

2.3 Participants

The experiment consisted of fifty-six participants and all fulfilled the requirements of possessing a valid driver's license, having a minimum age of 18 years and proficient German skills. The latter was important to minimize misunderstandings of the designed HMI. All participants were randomly allocated to the two groups, i.e. "Input Allowed" and "Input Blocked", which had 28 participants in each case. The sample consisted of 17 female and 39 male participants with an average age of 25.64 years (SD = 4.75), ranging from 18 to 50 years. Two participants in the "Allowed" group anticipated the obstacle even before a transition was initiated and took over manual control for the "MRM evasive" scenario. They were assigned as not intervening participants for the analysis of the number of interventions and excluded from the remaining analysis.

2.4 Experimental Design and Dependent Variables

This study used a between-subject design with the control authority, i.e. driver input being allowed or blocked during an MRM, as the independent variable. Conditions to disengage automation for the allowed group were braking, accelerating, or pressing a button on the steering wheel. Due to the implementation of the automation, it is not possible to distinguish an applied steering angle between the driver and automation during the drive. Therefore, a steering angle condition would also disengage the automation during the "MRM evasive". For the blocked group, automation would not disengage until the vehicle is close to standstill. However, the steering wheel was not decoupled in order to not communicate a malfunction and could be turned by applying high counterforces. Every participant experienced both scenarios with the sequences permuted.

Dependent variables were the decision to intervene and if they intervened, the time and manner of intervention. An intervention was defined as any brake or gas pedal input or a difference of the steering angle over time greater than 2 degrees*second between the participant's maneuver and the MRM, while driving faster than 10 km/h. Furthermore, the criticality of the encountered situation due to an intervention was assessed by the TTC to other road users and accidents. The intervention was classified as dangerous if the TTC was below 2 s or the distance was less than 54 m. These rules are part of driver training in Germany, where a fine can be issued if the driver falls below the named distance.

Due to technical issues, the distance data to road users in the middle lane could not be completely recorded and were therefore reconstructed in case the participants decided to overtake on the left. Thus, the time it took the ego vehicle to change lanes to the middle lane was retrieved from the participant's data. This time was used to calculate the new positions of other traffic participants, since they were always located behind the ego vehicle and drove at a constant velocity of 108 km/h. Consequently, the distance and

TTC to these traffic participants could also be calculated. Video material was watched subsequently by the investigator for verification.

Re-entering into traffic was analyzed via the ego vehicles' trajectories of those participants who did not intervene in an MRM and came to a full stop. In addition, subjective data was collected by a semi-structured interview and questionnaires.

Statistical tests were carried out in JASP (Version 0.14) with a significance level of $\alpha = .05$. Data analysis was conducted in MATLAB (The MathWorks Inc.) and Excel (Microsoft Inc.).

2.5 HMI

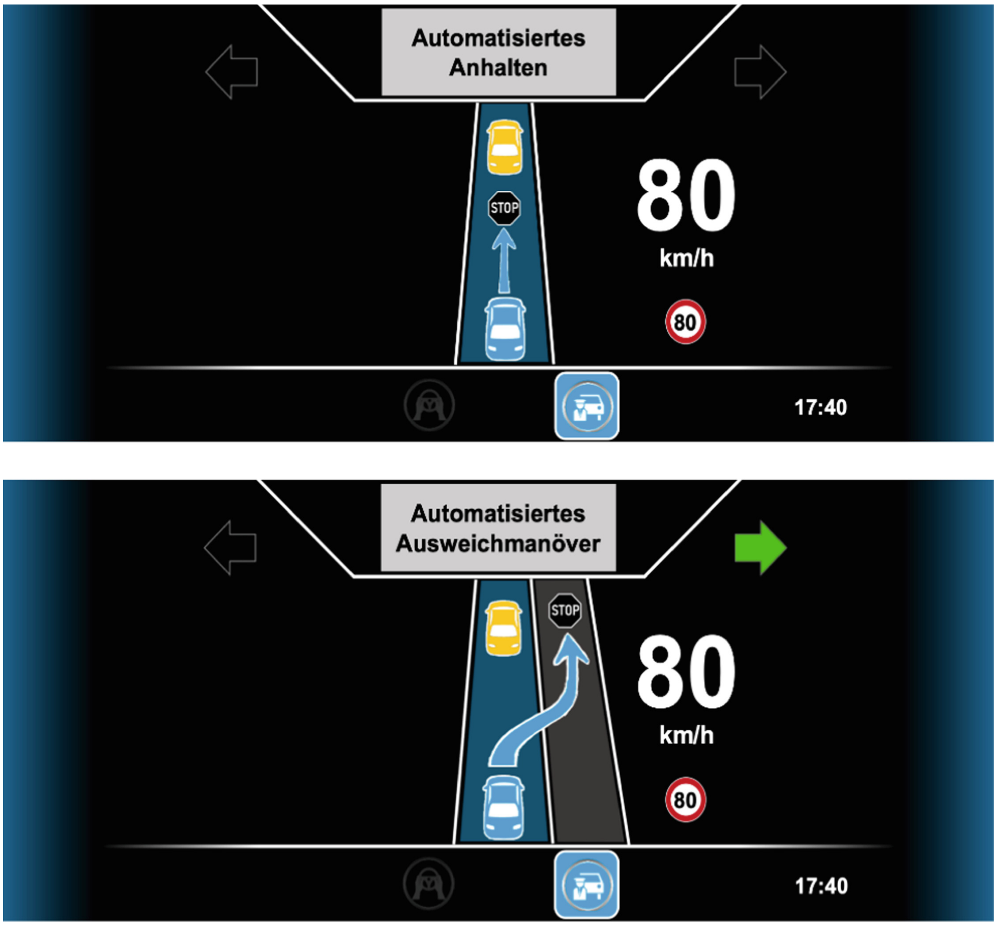

Fig. 1. Information on the IC during the transition phase with (I) "MRM stop" and (II) "MRM evasive". Grey boxes mean translated (I) "Automated Stop" and (II) "Automated Evasive Maneuver" (from top to bottom).

The HMI for this study was designed primarily for the transition phase to communicate relevant information regarding the upcoming MRM. Therefore, an existing HMI concept from [7–10] served as the basis and was adapted to our use case.

As soon as the obstacle is detected, the AoM is triggered and marks the beginning of the transition phase. It consists of visual and acoustic information. Visual information is shown on the IC in addition with pulsing blue edges at 1 Hz (see Fig. 1). Acoustically, two beep sounds are played followed by a computer-generated speech output with a female voice in German. It either contains the translated message “automated stop in the own lane” or “automated evasive maneuver to the right”. Both acoustic messages have an approximate duration of 3 s. Without interventions, both maneuvers come to a standstill and the automated system requests to continue driving manually by displaying a grey text box and activated hazard lights at the top of the IC.

A short quiz between the training and experimental drives was conducted to ensure that participants understood the HMI correctly. Participants were asked about perceived visual and audio messages and their meaning, and were corrected in case of wrong answers.

3 Results

3.1 Number of Interventions

As shown in Fig. 2, participants intervened regardless of their group, but more interventions were performed in the “Allowed” group. The number of interventions for the “MRM evasive” and “MRM stop” were approximately the same within each group. The proportion of intervening drivers for both of these MRMs was 25.00% in the “Allowed” group and 17.86% in the” Blocked” group. In contrast, this proportion was nearly three times larger for at least one of the MRMs, i.e. 71.43% in the “Allowed” group and 57.14% in the “Blocked” group.

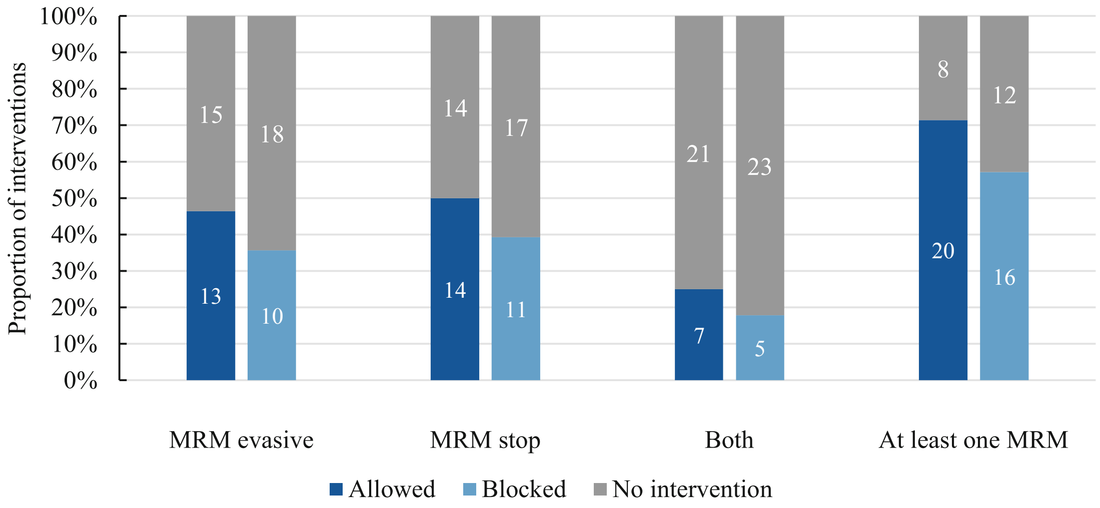

Fig. 2. Number of interventions per group and MRM.

3.2 Manner of Intervention

Participants of both groups clearly favored intervention by maneuvering to the left (see Fig. 3). One participant in each group decided to slowly overtake by using the shoulder lane during the “MRM evasive” scenario. Furthermore, the maneuver to the left started during the evasive MRM in both groups only after the vehicle started to steer to the right.

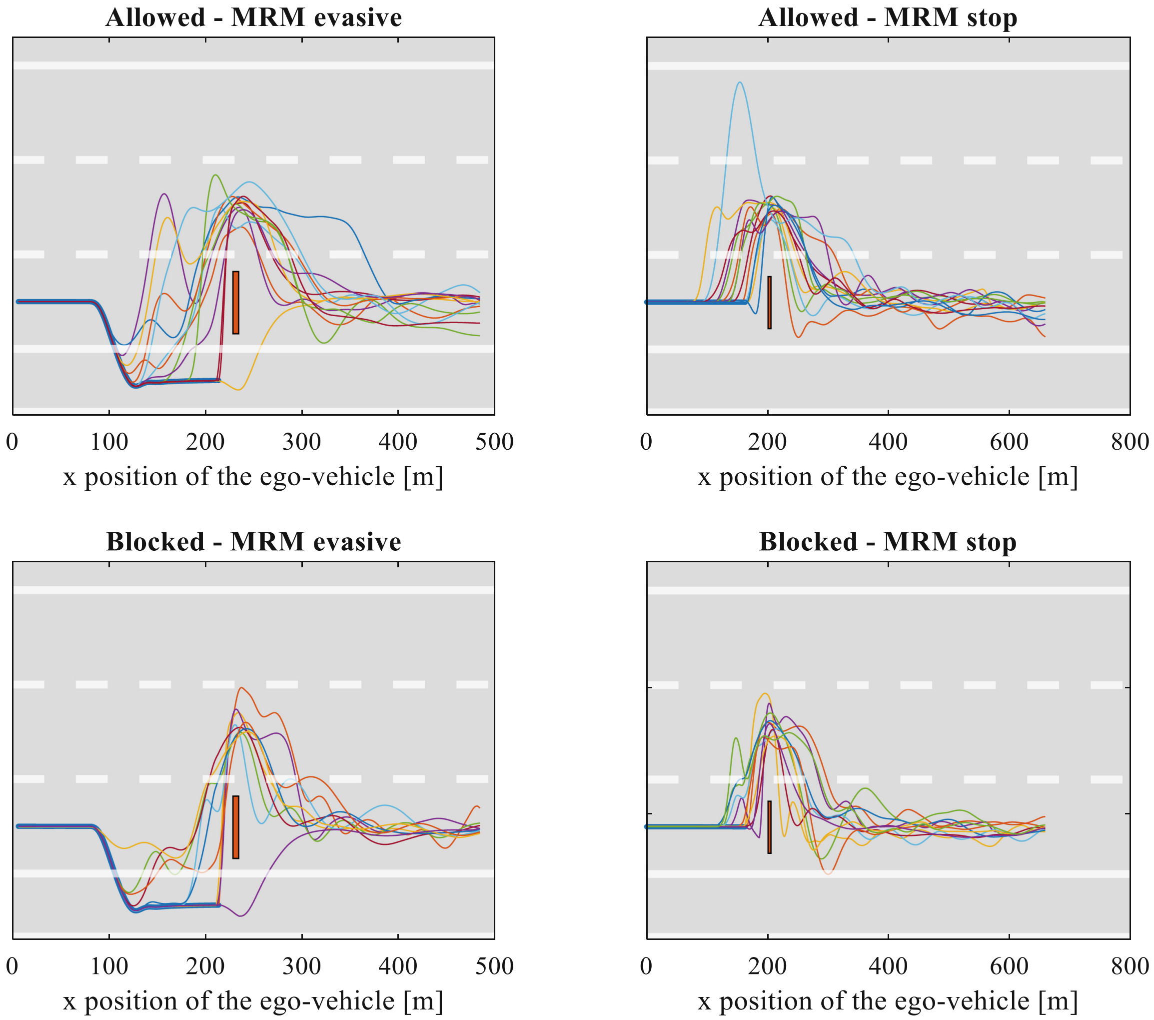

Fig. 3. Ego vehicle trajectories of participants who intervened during the transition phase. The blue thick line represents the trajectory that the automated system follows for the respective MRM. The AoM was triggered at 0 m.

3.3 Time of First Intervention

Every participant performed his/her first intervention after the AoM was finished except for one participant in the "Allowed" group and during the "MRM Stop" scenario (see Fig. 4). In this individual case, the participant noticed the obstacle before the AoM was triggered and took over manual control with one hand while holding the tablet in the other hand.

To exclude random effects, although the scenario order was permuted, the time of the first intervention between the first and second scenario was analyzed within a group via a paired samples t-test. In the "Allowed" group, no significant difference between the first ($M = 6.47$, $SD = 2.50$) and second scenario ($M = 6.12$, $SD = 1.84$) was found ($t(12) = 0.67$, $p = .515$). Also, no significant difference between the first ($M = 5.91$, $SD = 1.62$) and second scenario ($M = 5.56$, $SD = 1.46$) was found ($t(6) = 0.952$, $p = .378$) in the "Blocked" group.

Furthermore, differences between the time of first intervention during the "MRM evasive" and "MRM stop" scenario were analyzed with a paired samples t-test and showed no significant results in the “Allowed” (“MRM evasive”: $M = 6.28$, $SD = 2.19$, “MRM stop”: $M = 6.29$, $SD = 2.18$; $t(12) = 0.299, p = .770$) as well as in the “Blocked” group (“MRM evasive”: $M = 5.65$, $SD = 1.59$, “MRM stop”: $M = 5.70$, $SD = 1.46$; $t(9) = -0.066, p = .949$).

Therefore, the times of first intervention during the “MRM evasive” and “MRM stop” scenario within a group were combined to compare between the “Allowed” ($M = 6.29$, $SD = 2.14$) and “Blocked” group ($M = 5.68$, $SD = 1.45$). An independent samples t-test showed no significant difference ($t(46) = -1.112, p = .272$).

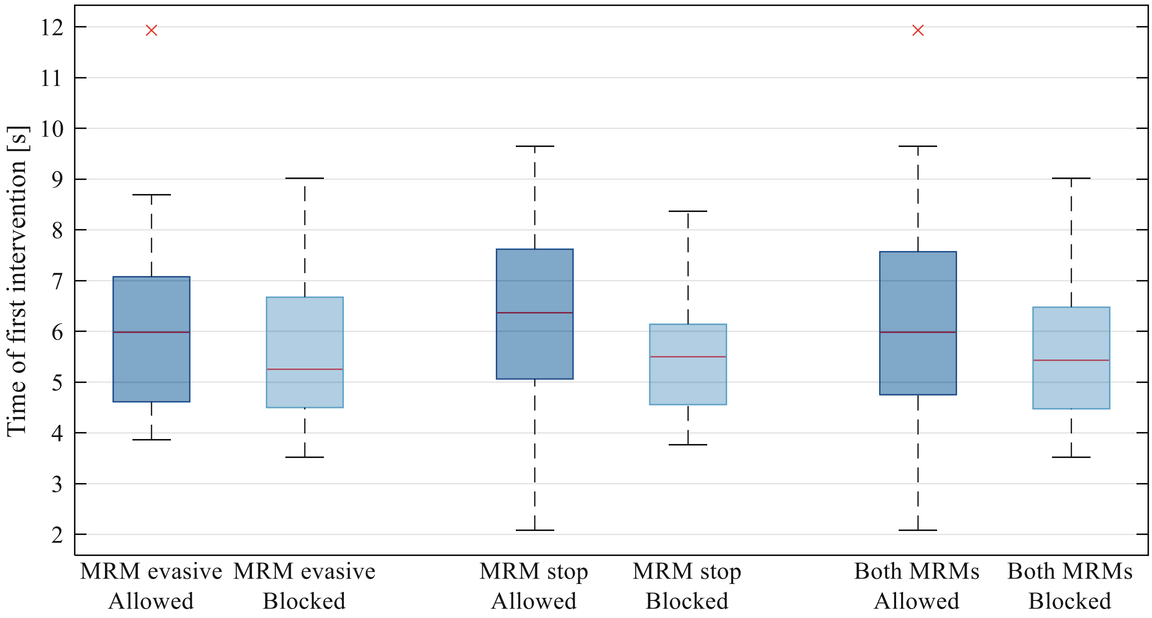

Fig. 4. Time of first intervention after the start of the AoM.

3.4 Criticality Because of Driver Intervention

None of the participants had an accident with the obstacle causing the MRM. However, several critical situations occurred due to maneuvering to the left, i.e. the middle lane. Approaching vehicles were not always detected, leading to one accident in the “Allowed” and three accidents in the “Blocked” group. Two dangerous situations as defined in Sect. 2.4 occurred in the “Allowed” group. Additionally, one participant ended up in another dangerous situation due to performing two lane changes and getting to the median strip, approximately 20 cm from the guardrail (see also Fig. 3). Two participants in the “Blocked” group got into dangerous situations as well.

3.5 Reasons for (Not) Intervening

On the one hand, participants stated that the reasons for their intervention were because of a disagreement with the MRM strategy by the automated system (67%), not trusting the automation (13%), not having enough time (13%) or not trusting other vehicles (7%). On the other hand, not intervening was justified since the non-driving related task was too distracting (32%), since there was not enough time for a decision (28%), since they did not trust the automation (20%) or since they did not perceive the situation urgent enough and since they wanted to observe the automated vehicle's response (20%).

3.6 Re-entering into Traffic

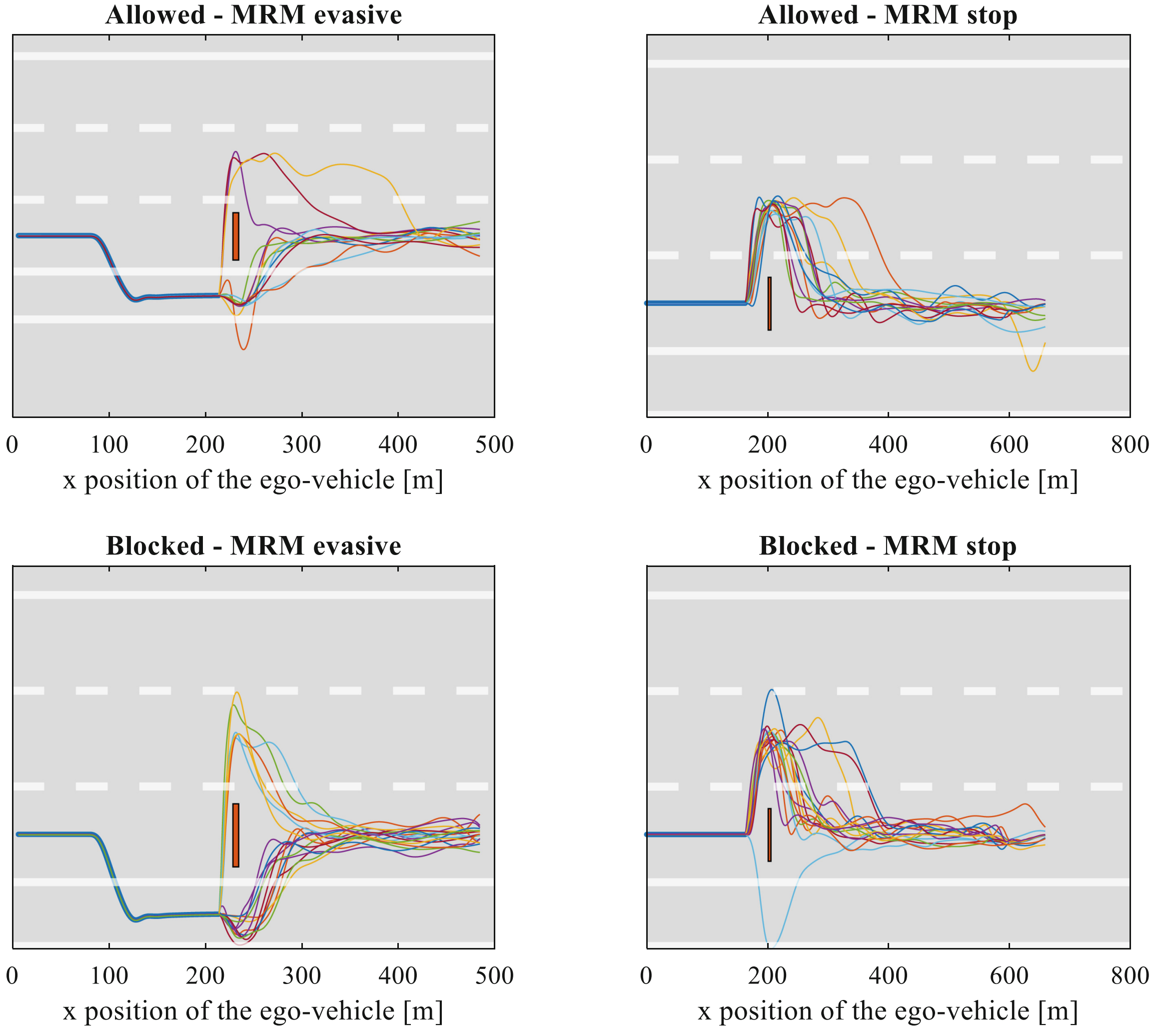

Fig. 5. Ego vehicle trajectories of participants re-entering into traffic after the MRM is finished. The blue thick line represents the trajectory that the automated system follows for the respective MRM. The AoM was triggered at 0 m.

Accelerating from a standstill position and re-entering into traffic happened only into the middle lane during the "MRM stop" scenario except for one participant in the "Blocked" group. Even in the "MRM evasive" scenario, two lane changes were accepted by participants in both groups in order to not have to overtake the obstacle by means of the shoulder lane (see Fig. 5).

4 Discussion and Conclusion

The results of our research show that the proportion of drivers intervening in an MRM is high regardless of their authority. Furthermore, participants in the “Blocked” group overcame the counterforces on the steering wheel to accomplish their desired maneuver.

We confirmed the study results of the video-based experiment from Karakaya et al. [6], where participants preferred a maneuver to the left over right and standstill. Except for two participants, everyone decided to overtake the vehicle on the left even though it would require one or two lane changes. It seems that driving in an emergency lane is avoided by any means. According to the self-stated reasons for intervention, disagreement with the MRM strategy was the main reason. The possible explanation could be traffic law and driver education in Germany, where driving on the shoulder lane is only allowed in case of an accident or emergency. This in turn means that drivers do not assess the presented situations critically enough.

According to our analysis, the order of the two implemented MRM strategies and the strategy itself do not have an impact on the time of the first intervention within a group. Also, no difference was found between the two groups. Consequently, drivers perform their first intervention regardless of the MRM strategy and control authority. The first intervention was made on average 6 s after the start of the AoM, which in turn means that participants intervened after the AoM was finished (approximately 3 s) in the case that the obstacle was not independently detected.

Investigating MRMs requires not only an analysis of the transition phase but also of the process of re-entering into traffic. Results show that even for that purpose, drivers avoid the shoulder lane and accept an overtaking maneuver at low speed through the middle lane. These results may be different for naturalistic driving studies and should be explored further.

In conclusion, the risk of an imminent collision was not reduced by introducing MRMs and simply allowing or disallowing driver intervention under the experimental conditions and based on our results. With intervention rates up to 70% in at least one of the MRMs during a 25 min drive, we can expect that drivers will tend to take over manual control in the future as well. This in turn leads to the known problems of transition phases of level 3 automation [11, 12] that were observed in our study. Therefore, more countermeasures need to be taken in the future.

Acknowledgment. This research was conducted within the project “CADJapanGermany: HF” which is funded by the Federal Ministry of Education and Research of Germany. We would like to acknowledge Zehui Cheng for his assistance in data collection. The experiment was approved by the Ethics Commission of the Technical University of Munich.

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Minimal Risk Maneuvers of Automated Vehicles: Effects of a Contact Analog Head-Up Display Supporting Driver Decisions and Actions in Transition Phases

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Abstract: Minimal risk maneuvers (MRMs), as part of highly automated systems, aim at minimizing the risk during a transition phase from automated to manual driving. Previous studies show that many drivers have an urge to intervene in transition phases despite the system's capability to safely come to a standstill. A human–machine interface (HMI) concept was developed to support driver decisions by providing environmental information and action recommendations. This was investigated in a static driving simulator experiment with 36 participants. Two scenarios that differed in the traffic on the adjacent left lane were implemented and the HMI concept displayed the content accordingly. Results of the study again show a high intervention rate of drivers overtaking the obstacle from the left, even if the lane is occupied by other vehicles. The HMI concept had a positive influence on the manner of intervention by encouraging a standstill in the shoulder lane. Nevertheless, negative consequences included accidents and dangerous situations, but at lower frequencies and proportions during drives with the HMI concept. In conclusion, the risk during the transition phase was reduced. Furthermore, the results showed a significant decrease in the subjective workload and a positive influence on the drivers' understanding and predictability of the automated system.

Keywords: minimal risk maneuver; transition phase; highly automated driving; driver behavior; human–machine interface; contact analog head-up display

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Citation: Karakaya, B.; Bengler, K. Minimal Risk Maneuvers of Automated Vehicles: Effects of a Contact Analog Head-Up Display Supporting Driver Decisions and Actions in Transition Phases. *Safety* **2023**, *9*, 7. https://doi.org/10.3390/safety9010007

Academic Editor: Raphael Grzebieta

Received: 6 December 2022
Revised: 29 January 2023
Accepted: 31 January 2023
Published: 3 February 2023

1. Introduction

The human desire for mobility is a key driver for innovations. The first demonstration of a self-driving vehicle was first reported nearly 40 years after the invention of the automobile by Carl Benz in 1886. The "American Wonder" by Houdina Radio Control Co. rolled out in the summer of 1925 along Broadway in New York City and was trailed by radio waves from a following car. As enthusiastic as this sounds, it ended shortly after, when the driverless vehicle crashed into another passenger-filled vehicle [1]. Nevertheless, this small setback did not stop intensive research on this topic for the next nearly 100 years. Today, we can observe that automated systems developed from early prototypes to the first legally approved and commercially available vehicles, i.e., vehicles equipped with the "Traffic Jam Pilot" by Honda in Japan [2,3]. Unless a system functions fully autonomously, humans will always play a role as a part of that system, although with different roles. Therefore, it is important to consider the human factors in all fields where automation works together with human beings or vice versa. Research regarding every aspect of coexistence, cooperation, and collaboration [4] between humans and robots provided us with valuable knowledge on its effects. In the field of aviation, where automation currently plays a bigger role than in the automotive sector, known problems for pilots include the loss of skill, a greater workload, and the reduction or loss of situation awareness [5–8]. Increasing automation allows the driver to hand over the control and engage in a non-driving related task (NDRT). These effects can then also be observed in assisted and automated vehicles when system-initiated transitions of control are required [7]. Resulting take-over times and performance during these transition phases were intensively researched in recent years and approaches to model both can be found in [9,10]. All of these studies have in common that the driver is responsible to take over the driving task whenever the system reaches its boundaries. A promising approach for the next step of automated driving would be that drivers are no longer responsible for taking over and that automated systems achieve a safe condition instead.

1.1. MRMs and MRCs

As indicated above, handing over control and decoupling from the control loop allows drivers to engage in NDRTs, e.g., eating and drinking, reading, writing/tapping on the phone, etc. [11]. A widespread taxonomy by the Society of Automobile Engineers (SAE) provides six levels of driving automation and classifies this as an automation level 3 or higher [12]. Whenever the system triggers a take-over request, the driver of a level 3 system is mainly responsible to resolve the situation and must achieve a minimal risk condition (MRC). SAE defines an MRC as follows, whereby the abbreviations stand for automated driving system (ADS) and dynamic driving task (DDT):

> "A stable, stopped condition to which a user or an ADS may bring a vehicle after performing the DDT fallback in order to reduce the risk of a crash when a given trip cannot or should not be continued." [12] (p. 15)

Since the latest update of the document in April 2021, the condition was more exactly specified by adding the terms *stable* and *stopped*. If the vehicle is capable to achieve this state under all circumstances within its operational design domain (ODD), i.e operating conditions of an ADS such as geographical, (traffic) environmental, and daytime conditions, it can be classified as a level 4 system. In contrast, driver action is mandatory for level 3 systems since achieving the MRC cannot be guaranteed, although it is equally possible. Furthermore, an ADS at level 4 or above may allow driver intervention during the transition process but can also be designed to even disallow it for the purpose of crash risk reduction. Even if the term is not explicitly defined in the taxonomy, a maneuver that is required to achieve an MRC either by the driver or vehicle is called a minimal risk maneuver (MRM). Examples of MRCs are a standstill on the vehicle's own, adjacent or, if existent, shoulder lane with the respective MRMs braking and/or steering to the slower lanes. The SAE follows the same principle for transition phases with or without an automatic MRM: an alert to the passenger of a level 4 system or a request to intervene for level 3 systems, both marking the beginning of a transition phase.

In a document from the Federal Highway Research Institute of Germany (BASt) from 2012 an MRC is stated as a vehicle in standstill [13]. The transition to this state takes place after the driver did not respond to the request to intervene in time. Corresponding maneuvers depend on the traffic situation, state of the automation system and risk. Even if the risk assessment is not further specified, the maneuver with the lower risk should be selected. Possible MRMs include braking until standstill in the vehicle's own lane or a neighboring hard shoulder coupled with a lane change. Drivers are able to overrule and cancel an MRM at any time via the brake/gas pedal or steering wheel input or by means of a switch. This document will not be further described, since other definitions regarding automated functions or levels have been changed. Newer publications from 2017 and 2020 introduce the *Principles of Operation* that allows a more precise classification of automated functions. Here, MRCs can be found under the *Principle of Operation C*, which describes functions that temporarily intervene in accident-prone situations [14,15]. These functions can be overruled by the driver to ensure controllability. The term MRC or risk-minimal state appears for functions at level β_I and γ_I in the case of an abstract hazard, when the driver does not perform according to expectations and no immediate collision is apparent. The vehicle reaches the MRC either in the short term without a full overview of the respective traffic situation (β_I) or fully takes over control (γ_I). During situations with concrete hazards, functions at level γ_{II} are also able to take over control and fluently transition to β_I or γ_I if driver takeover remains absent. An MRC was not further specified.

The United Nations Economic Commission for Europe (UNECE) adopted the Regulation No. 157 in early 2021 which specifies Automated Lane Keeping Systems (ALKS) at an operating speed up to 60 km/h. After activation by the driver, these systems take over longitudinal and lateral control of the vehicle and perform MRMs automatically after a transition demand in the event of severe failures or absence of driver input. The desired state to be reached by the MRM is standstill unless the driver deactivates the system during this process. The latter is favored and tried to be enforced by warning cascades no later than 4 s after the start of the transition demand and triggers an MRM at least after 10 s. In contrast to emergency maneuvers, MRMs shall not decelerate any faster than 4.0 m/s^2 [16].

According to ISO 26262, an MRM can be seen as an emergency operation that is an operating mode for providing safety as a reaction to a failure until the transition to a safe state [17] (p. 9). The international standard names the example of a switched-off mode for a safe state. A white paper from 11 companies in the field of automotive and automated driving adopt this definition and extend it with more MRCs in addition to standstill, i.e., a takeover by the vehicle operator and a limited operation condition [18]. This concept allows multiple MRCs along the way to the final one with corresponding MRMs, i.e., a transition demand, a limit function state (transition to the MRC "limited operation"), various stop maneuvers (comfort, safe and emergency stop), and recovery (reaching the nominal state again).

Summing up the literature, MRMs and MRCs are described from the system perspective even though drivers are assigned an important role during this process–namely primarily to overtake control even though it is not mandatory. A common MRC is a vehicle standstill either in it's own or adjacent free lane with the respective maneuvers: lane change (if applicable) followed by braking. In combination with a driver in the vehicle that is able or even requested to take over, driver actions during transition phases should be considered in the risk assessment. The need for including the human as a factor is shown by Karakaya et al. [19], who investigated this topic from the driver's point of view. In this lab study, 49 participants were invited and shown videos of the first possible maneuver in five different scenarios, resulting in 14 maneuvers in total. The applied method ensured a safe and sober view on MRMs and MRCs. Participants were asked to rate the perceived risk and choose the safest maneuver within scenarios. Results show that drivers prefer different MRMs than the literature's guidelines or regulations, i.e., evasive maneuvers over braking until standstill and more importantly overtaking maneuvers from left over right. This discrepancy of intentions could lead to a driver counteracting the automated system and was investigated further by an experiment from Karakaya and Bengler [20]. In the experiment, 56 participants experienced transition phases with two MRMs on a three-lane highway, i.e., standstill on far right lane and one lane change to the shoulder lane coupled with a standstill. Drivers were instructed that no action was required during transition phases because of the system's capability to perform these MRMs. Nevertheless, drivers were either allowed to intervene in the maneuver or their input was blocked. The latter was implemented by blocking any gas or brake pedal input, although the steering wheel turned according to the system's maneuver in order to not communicate a malfunction. Despite the need for high counterforces to change the vehicle's direction in this group, more than 50% of the participants intervened in at least one of the two MRMs. The same number of interventions in the other group was more than 70% with the favored maneuver being to overtake the obstacle from the left, in this case through the middle lane. Interventions resulted in four accidents and five dangerous situations with the following traffic in the middle lane. Main reasons for an intervention were a disagreement with the MRM strategy (67%) and a lack of trust (13%). It can be derived from both studies that the discrepancy of intentions for a maneuver between the automated system and the driver during a transition phase is not only apparent but also leads to interventions by the driver no matter the hurdles. Furthermore, these interventions can cause (near) collisions with other traffic participants and raises the question: Was the risk of an accident reduced by introducing MRMs in transition phases? Solutions could be an intervention with a hazard-free maneuver or, under the premise of a flawless MRM, no intervention at all.

1.2. Research Questions

In order to face the challenge of transition phases with MRMs, we defined the following research question for this study:

> Does environmental information and an action recommendation to the driver reduce the risk of an accident or dangerous situation during a transition phase with MRMs?

Additional information to drivers during a time critical transition phase between automation levels can have positive as well as negative effects and was addressed by the following research question:

> Does environmental information and an action recommendation to the driver affect their trust in automated vehicles and workload?

2. Materials and Methods

2.1. Scenarios and Transition Design

Two scenarios were implemented in the simulation that only differed in the presence of traffic in the middle lane, i.e., either with or without traffic (in the following referred to as the *occupied* or *free* scenarios). Both occurred on a three-lane highway with a shoulder lane while the ego vehicle was driving automated going 80 km/h in the right lane (see Figure 1). At a TTC of 11 s, a stranded vehicle with activated hazard lights caused the transition phase and the vehicle continued driving automated for 6.5 s, giving the driver time for a voluntary take-over. Automation either continued to perform an MRM, i.e., a lane change to the shoulder lane followed by braking until standstill, or disengaged in the case of driver intervention. A brake acceleration of 6 m/s^2 was applied and resulted in a duration of 8.1 s for the MRM.

During the *occupied* scenario, traffic on the middle lane consisted of a convoy traveling at approximately 120 km/h and the first vehicle was located 16.5 m behind the ego vehicle. Six following vehicles had a distance of 20 m between them. The lane width was 3.75 m except for the shoulder lane, which was 2.5 m.

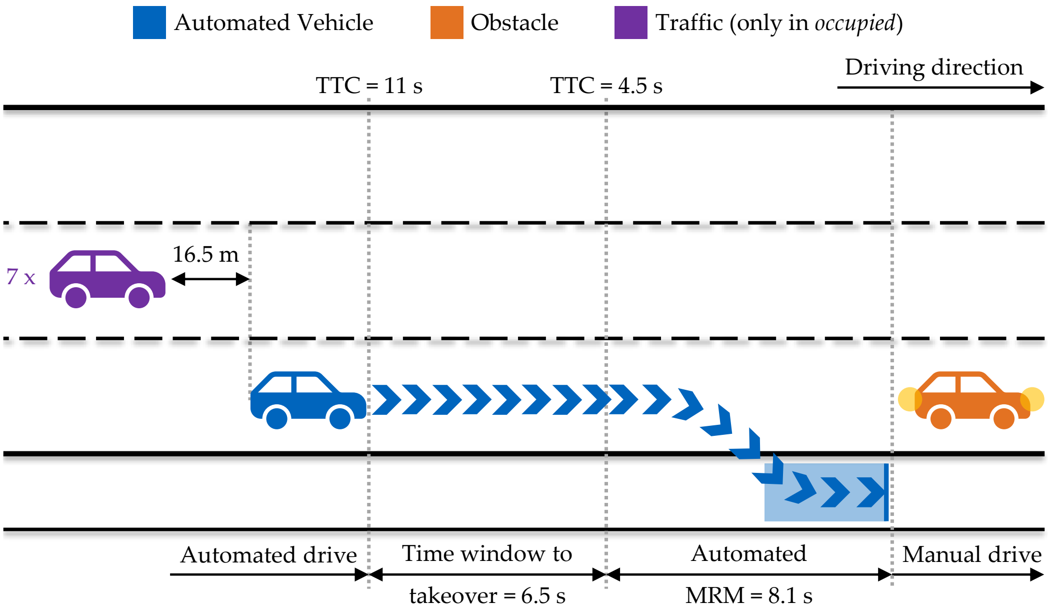

Figure 1. Schematic illustration of the transition design and two scenarios (*free* and *occupied*).

2.2. HMI Design and Preliminary Study

2.2.1. Theoretical Background

The underlying problem of risky transition phases and the reasons for it are described in Section 1.1 and mainly occurs if drivers intervene in an MRM and are subsequently situated in a riskier condition than they would be if they let the ADS perform its maneuver. To prevent a risky maneuver by the driver, it is important to understand the process to this point, which can be roughly described applying the information processing model by [21]: *sensory processing*, *perception*, *response selection*, and *response execution*. Other parts of the model, such as the system environment, which forms a closed feedback loop, the attention resources, long-term memory, working memory and cognition have their influence on this "four-stage + memory model" [21] (p. 5). Analogous to this process, Parasuraman et al. [22] divided automation into four classes of functions: *information acquisition*, *information analysis*, *decision and action selection*, *action implementation*. Functions of an automated system can be allocated within a category on a scale from low to high. Eriksson et al. [23] argue that interfaces addressing these categories would score with respect to its design, e.g., providing information about the traffic situation [24] would score high in the *information analysis* category, whereas suggesting actions [25] would score high in the *decision selection* category. It is expected that the outcome of the driver's information process, i.e., *response execution*, benefits from previously provided and well-designed information via the human machine interface (HMI) [25–28].

The focus of this study is an investigation from the driver's perspective, i.e., within the vehicle. Furthermore, the approach is to use communication between the ADS and driver as a tool to improve transition phases with MRMs. According to the HMI framework by Bengler et al. [29], we are operating within the *Automation HMI (aHMI)*. In the case of modalities, haptic and auditory signals are mainly used for warnings, whereas the visual modality was mainly applied for representing the automation state and results of the automation's *information analysis* and *decision and action selection* processes [29]. The following hardware is frequently used as a visual interface: instrument cluster, monitor in center console, (augmented reality) head-up display, and LED-strip in the windshield [29]. A contact analog head-up display (cHUD), can be seen as an extension of augmented reality since virtual information is displayed at the correct location in the real environment [30] (p. 20). In general, the benefits of such systems are:

- Parallel interpretation of displayed information and traffic environment [25]
- Quick and controlled drawing of attention towards relevant areas [31]
- Increase in user acceptance [32,33]
- Helps to rebuild situation awareness [26]
- Improve gaze behavior [33,34]
- Increase in trust in automation [32,34]
- Decrease in subjective workload [27,34]

Despite designing an ergonomic cHUD, negative effects can still occur, such as masking other driving related areas [35,36], causing the effects "cognitive capture" [35,37] and "attentional tunneling" [38], etc. Consequently, driver action can be directed both ways and unexpected results are possible, e.g., cHUD causing unnecessary braking due to highlighting objects in traffic with spheres [23]. With regard to our research objective, the relevant application areas of cHUDs are:

1. Maneuver recommendations in the form of carpets/corridors [23,27,28]
2. Maneuver recommendations in the form of arrows [23,26]
3. Maneuver information or planned trajectories in the form of arrows [32–34]
4. Highlighting objects in the (traffic) environment [23,33,34]

Results of studies show improvements in drivers' decision making and maneuver success [23], reduction of accelerations and time to lane change [26], and improvement of the quality of drivers' actions [27,28].

A multi-modal approach with at least two feedback modalities is recommended [39] (p. 269) and especially the combination of visual and auditory modality was commonly applied in studies with transition phases between different levels of automation [40] and with MRMs [20,41]. Based on these findings from the literature, the instrument cluster plus cHUD for the visual and sounds along with voice message for the auditory modality were chosen for the first HMI concept.

2.2.2. Preliminary Study

The first HMI concept was assessed via an expert evaluation built on the HMI checklist by Schömig et al. [42]. For this purpose, six experts in the field of interface design for automated driving from the Chair of Ergonomics at the Technical University of Munich were recruited. Due to hygiene restrictions caused by the COVID-19 pandemic, an online format was decided on and materials accordingly prepared. In the first round, the study investigator introduced the topic and study design. Afterwards, each phase during the experimental drive together with pictures of the simulated track was gone through and respective HMI elements, i.e., the instrument cluster, cHUD, and auditory signals, were presented. In the second round, the same procedure took place but with experts being instructed with respect to giving feedback. The checklist [42] was accordingly filled out by the study investigator and rating categories (*major concerns*, *minor concerns*, *no concerns*, *measurement necessary*, *not applicable*) regarding the 20 heuristics were documented. Except for the heuristics in Table 1, the results of the expert review were either categorized as *not applicable* or *no concern*. None of the heuristics was evaluated as *measurement necessary* due the proposed HMI design building on existent concepts and standards.

Table 1. Results of the expert review about the first HMI concept.

Number of Heuristic	Description of Heuristic	Results of Expert Review
2	The system mode should be displayed continuously	minor concerns
3	Mode changes should be effectively communicated	minor concerns
15	Design for color-blindness by redundant coding and avoidance of red/green and blue/yellow combinations	minor concerns

Remarks by the experts related to the instrument cluster resulted in changes in icon properties, i.e., background color and level of transparency, as well as permanently displaying neighboring lanes. Regarding the cHUD, the length of the green carpet was extended and marking of the obstacle was adjusted to be more salient. The last remark concerned the red/green coding, which was not changed due to established indicators for warnings but was considered during the participant recruitment.

2.2.3. HMI Concept

The final HMI concept as it was implemented for this study consisted of visual (instrument cluster and cHUD) and auditory (sound and voice message) elements, primarily designed for a transition phase with an MRM (see Section 2.2.1).

During the baseline and experimental drive, participants experienced the transition phase with the same information in the instrument cluster (see Figure 2d) and auditory messages, i.e., two beep sounds followed by a computer-generated voice message with a female voice in German. The voice message can be translated as "automated evasive maneuver to the right". Total duration of the auditory messages were approximately 3 s. In addition, the planned trajectory of the ADS is shown via blue arrows. The space in which the vehicle will come to a standstill is marked with a blue carpet on the lane (part of it can be seen in Figure 2c). In the case of no intervention, the vehicle performs the MRM with right indicator plus the translated message in the instrument cluster "DO NOT INTERVENE!" in red font. Hazard lights are turned on and the message "Please continue driving manually" is displayed after coming to a standstill. The planned trajectory disappears as soon as the driver intervenes and the automation shuts off.

Only during the experimental drive, the recommendations for a voluntary take-over were shown in the *free* scenario in the form of a green carpet on the left lane (see Figure 2a). Consequently, the shoulder lane was recommended and the occupied lane indicated through a red line or narrow carpet in the *occupied* scenario (see Figure 2b). Contrary to the planned trajectory, the recommendations were still shown in the event of an intervention.

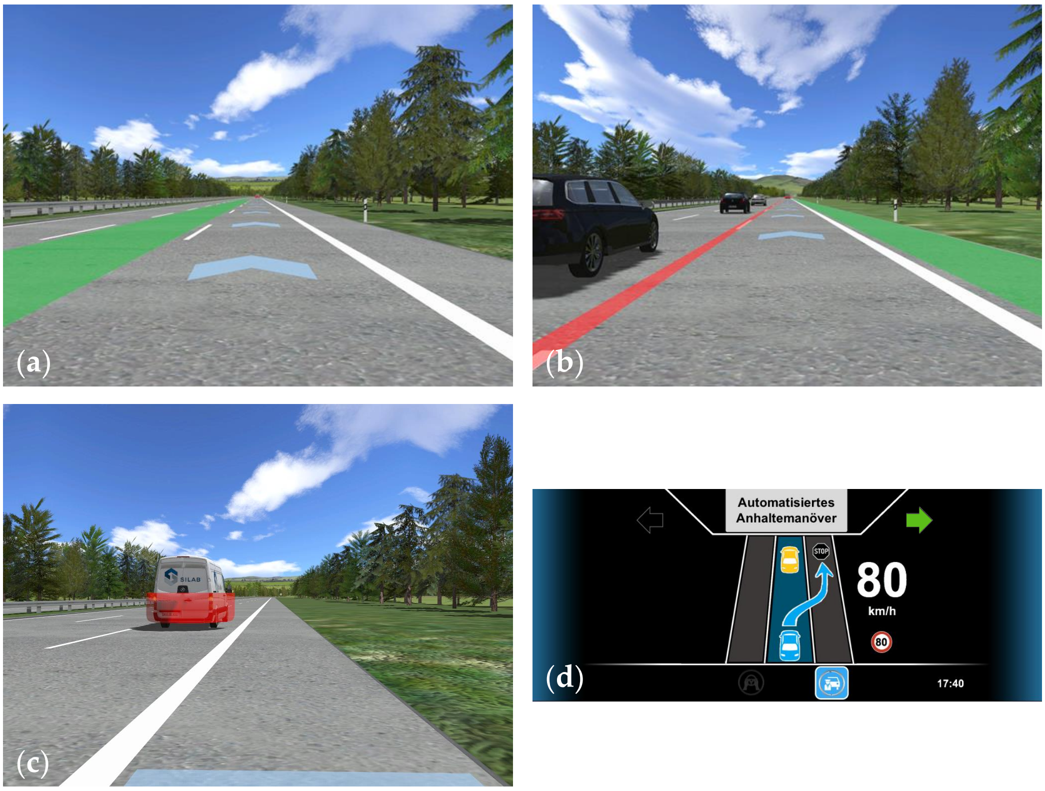

Figure 2. Visual elements of the HMI concept as implemented in this study, showing the cHUD during the (**a**) *free* and (**b**) *occupied* scenario for the experimental drive. For both groups, (**c**) the highlighting of the obstacle was implemented in the form of brackets and (**d**) the instrument cluster contained the pictured information (blue edges pulsing with 1 Hz) during the transition phases.

2.3. Experimental Design

A within-subject design was used to minimize the individual influence of participants and ensure a comparison of both concepts. The participants took part consecutively in the baseline as well as experimental drive with the corresponding HMI concepts that only differ in the recommendations shown for a voluntary takeover: HMI BL and HMI REC (see Section 2.2.3). Both drives started with a manual drive and participants had to activate the ADS as soon as they entered the highway, which was signalized by the system. Drivers were engaged in the game *"1010!"* by Zynga Inc. as a NDRT on a handheld device and experienced two transition phases during the *free* and *occupied* scenarios within 15 min of automated driving. Order of drives and scenarios within a drive were permuted and participants were randomly assigned.

2.4. Dependent Variables

Due to the transition design, the participants' driving performance could only be measured if there was an intervention. Therefore, the first dependent variable to investigate is the decision to intervene. Intervention is defined as any driver input on the brake or gas pedal, while steering angle change has to be evaluated, respectively, to the automated MRM, i.e., a difference of steering angle over time greater than 2 °s. If drivers chose to take over, dependent variables are similiar to those for assessing the take-over quality [10] and were the following:

- Intervention time: time span between the beginning of the transition phase and driver intervention
- Manner of intervention: standstill or overtaking maneuvers
- Time to lane change (in the case of an overtaking maneuver)
- Accelerations
- Criticality of intervention: accidents or dangerous situations

The process of re-entering into traffic is investigated if there is no intervention or standstill maneuver by the driver. Furthermore, data from questionnaires regarding subjective workload (NASA RTLX [43]) and trust in automation (TiA) [44] were collected. A semi-structured interview was conducted at the end of the experiment.

As mentioned above, the data set has missing values for some dependent variables, i.e., accelerations and the times for the first intervention and to lane change, since they are determined by the driver behaviour. A missing data point represents a missing intervention during the transition phases of drives. Statistical tests, such as repeated measures ANOVA, would treat missing values by listwise deletion and consequently distort the results. It is also possible that drivers may be inconsistent with their decision across transition phases, e.g., intervention only during the baseline drive, during different scenarios in each drive, etc., which would intensify this effect. Enhanced methods, e.g., linear mixed models, are not feasible due to the small number of data points. If applicable for the other dependent variables, statistical tests were conducted in IBM SPSS Statistics and JASP (version 0.16.3) with a significance level of $\alpha = 0.05$. Data preparation and descriptive statistics were carried out in MATLAB (The MathWorks Inc.) and Excel (Microsoft Inc.). Outliers in boxplots were values greater than the third quartile plus 1.5 times the interquartile range. The following hypotheses were formulated based on the presented literature:

Hypothesis 1a. *Providing recommendations for a voluntary take over does not influence the decision to intervene during the free scenario.*

Hypothesis 1b. *Providing recommendations for a voluntary take over reduces the number of interventions during the occupied scenario.*

Hypothesis 2. *Drives with the HMI REC result in a lower subjective workload than drives with the HMI Baseline.*

Hypothesis 3. *Drives with the HMI REC result in a higher trust in automation than drives with the HMI Baseline.*

2.5. Apparatus

The experiment was conducted on a static driving simulator equipped with five 55-inch ultra HD screens that allowed a 180° field of view (see Figure 3). Side mirrors are integrated in the form of two additional displays and rear view is placed on top of the middle screen. A freely programmable instrument cluster is located behind the steering wheel and audio speakers are attached around the mockup. Information through the cHUD was simulated by inserting the visual elements directly in the SILAB 6.0 simulation software from the Würzburg Institute of Traffic Sciences (WIVW). The experiment was video recorded via a GoPro HERO 6 on a tripod behind the driver seat. NDRT during the automated drive was performed on a 10-inch tablet from Huawei (Mediapad T3 10) that could be placed on a shelf to the right of the driver seat if manual control was resumed.

Figure 3. Driving simulator used in this study.

2.6. Participants

Requirements to participate at this study were a minimum age of 18 years old, a valid driver's license, and proficient German language skills to understand the HMI messages. In total, thirty-six participants with an average age of 25.86 years (SD = 9.53, Min = 19, Max = 65) took part at the experiment. The sample consisted of 13 female and 23 male participants. Due to technical issues, the automation did not turn off for two participants (scenario for both: *free*; drives: 1 × baseline and 1 × experimental) despite driver intervention and those data sets were partly excluded from the analysis, i.e., from driving performance and subjective data. One front screen of the driving simulator turned off close to the transition phase during the baseline drive for another participant and consequently this data set was excluded from the whole analysis for baseline drives. None of the participants reported uncorrected vision, color blindness, or hearing impairments.

2.7. Procedure

At the beginning, participants were welcomed, briefed on safety regulations, and instructed to read the information sheets regarding the experimental procedure. After signing the consent form and generating a pseudonymization code, a demographic questionnaire was filled out and participants were introduced to the driving simulator and automated system. Information on system boundaries and subsequent transition phases with MRMs were repeated, and it was emphasized that a take over by the driver is voluntary. Additionally, the planned trajectory of the automated system during this phase in the form of blue arrows as part of the cHUD was explained on a printed document. A training drive without other traffic participants and two transition phases followed, in which the participant was asked once to let the system perform the MRM and to intervene in the other. Depending on the permutation, the baseline or experimental drive followed. Prior to the experimental drive, the other parts of the cHUD, i.e., recommendations during the transition phase, were introduced the same way as before. Questionnaires about perceived workload and trust in automation were handed out after each drive and the experiment ended with a semi-structured interview. Total duration of the experiment was about 75 min and participants were compensated with an allowance of 30€.

3. Results

3.1. Driver Behavior in General During Transition Phase

First, driver behavior in general was analyzed during the transition phase and the results can be seen in Figure 4. Participants intervened during both scenarios and nearly two times more in the *free* scenario than in the *occupied* one. Consistent intervention decision can be derived from the number of interventions during both scenarios (HMI REC: 30.6%; HMI BL: 22.9%). From a safety perspective, an intervention during at least one transition phase is of interest, which was two to three times higher than interventions during both scenarios (HMI REC: 77.8%, HMI BL: 68.6%).

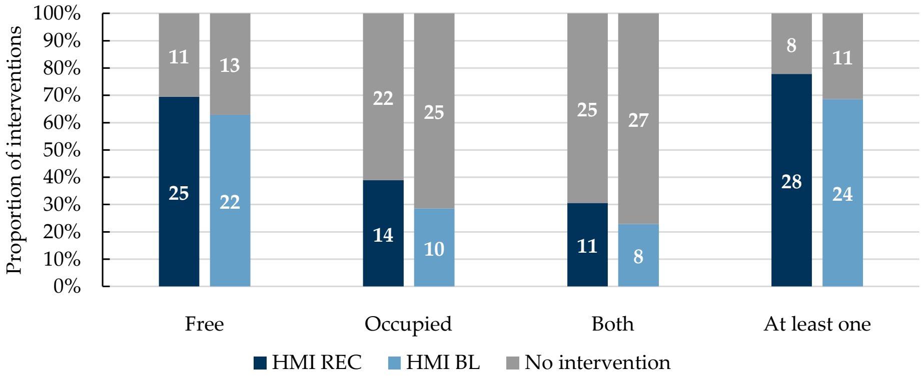

Figure 4. Number of interventions.

It can be assumed from these figures that in all cases, intervention rates with the HMI REC are higher than with HMI BL. An exact McNemar's test was conducted to test this assumption and showed no significant difference in the proportions during both scenarios (*free*: $p = 0.549$, *occupied*: $p = 0.344$). Corresponding contingency tables can be found in Table 2. Hence, hypothesis 1a can be accepted and 1b rejected. Note that one participant was excluded from the analysis due to missing data in the baseline drive as described in Section 2.6 ($n = 35$).

Table 2. Contingency tables on the decision to intervene during the *free* and *occupied* scenario.

Free	**HMI BL**		***Occupied***	**HMI BL**	
HMI REC	**No**	**Yes**	**HMI REC**	**No**	**Yes**
No	6	4	No	18	3
Yes	7	18	Yes	7	7

For the *occupied* scenario, different manners of intervention could be observed (see Figure 5). Participants favored overtaking the obstacle from the left (70%), although the middle lane was blocked by other traffic participants, over coming to a standstill in the shoulder lane (10%) and overtaking from the right (20%) during the baseline drive. The proportions change if maneuver recommendations are given via the HMI: the percentage of overtaking from the left is reduced to 21%, while coming to a standstill in the shoulder lane (50%) and overtaking from the right (29%) are increased. This results in a 50% willingness to follow the maneuver recommendation by the system.

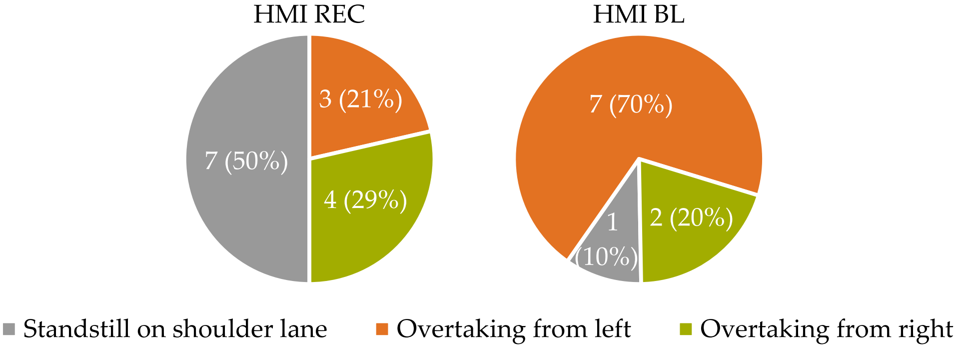

Figure 5. Manner of interventions during the scenario *occupied*.

In the case that participants intervened, the performed maneuver was solely an overtaking through the middle lane in the *free* scenario for both drives (see also Figure 6). Accordingly, all drivers followed the recommendation of the HMI REC.

3.2. Driving Performance of Intervening Drivers

The first intervention after the beginning of the transition phase in the experimental and baseline drive are similar within the *free* scenario, i.e., *M* = 4.07 s (*SD* = 0.97) and *M* = 4.28 s (*SD* = 1.28), and also the *occupied* one, i.e., *M* = 3.97 s (*SD* = 0.78) and *M* = 4.11 s (*SD* = 1.23) (see Figure 7). One participant intervened after the MRM had started in the *free* scenario during the baseline drive and is marked as an outlier. Nine interventions happened in less than 3 s, which means before the audio message was finished.

As shown in Figure 8, the values for the mean time to lane change with HMI REC in the *free* scenario are around 1 s slower than with HMI BL, with comparable standard deviations (5.50 s (*SD* = 0.95) and 6.63 s (*SD* = 1.27)). Mean values in the *occupied* scenario are higher with both HMI concepts, while HMI BL is higher than HMI REC (10.85 s (*SD* = 3.68) and 7.84 s (*SD* = 2.84)).

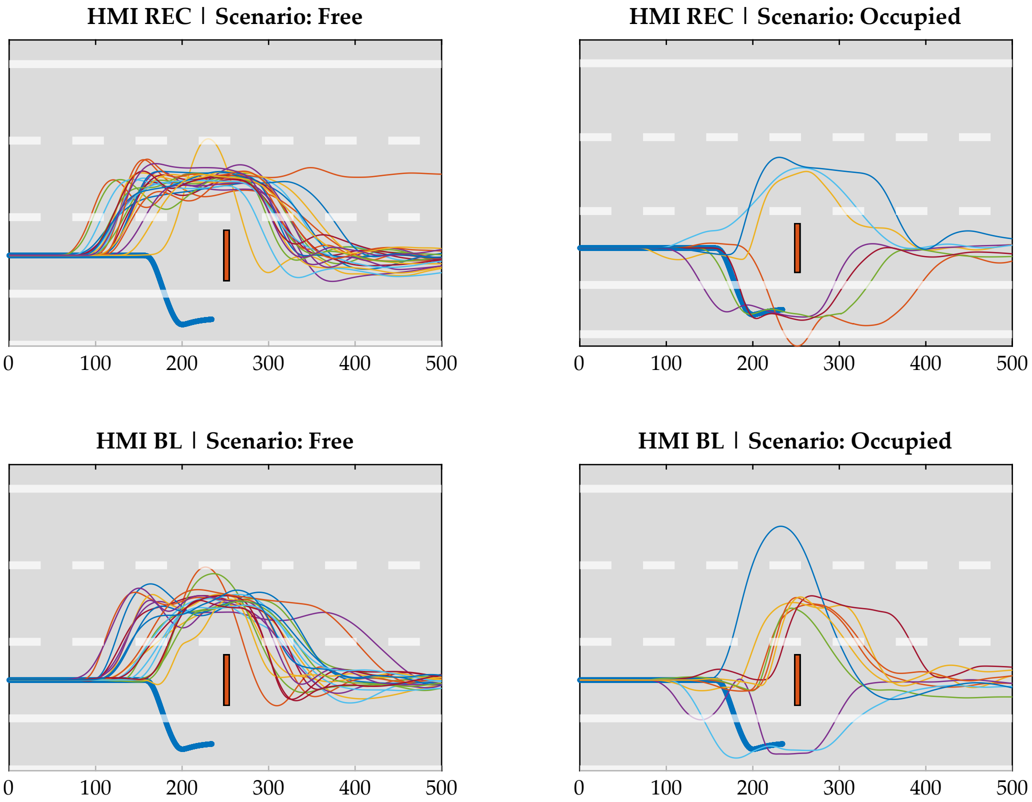

Figure 6. Trajectories of the center of gravity of the ego vehicle. The bue thick line shows the trajectory of the MRM and the transition phase starts at 0 m.

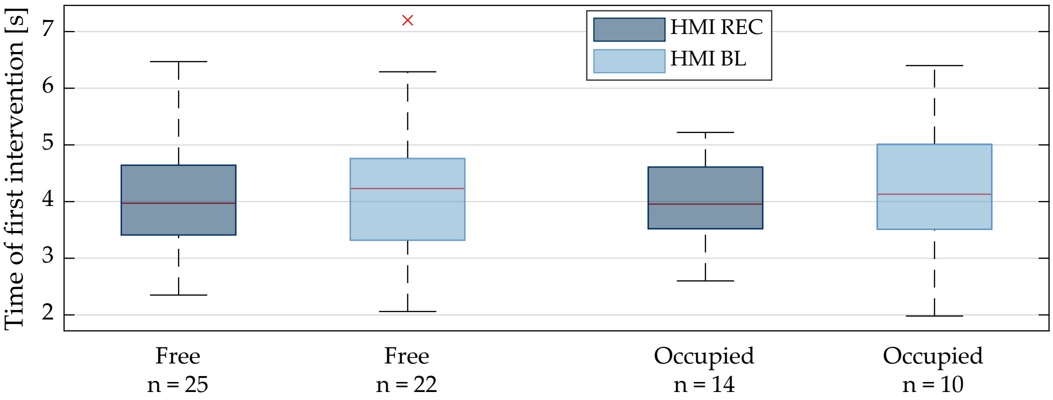

Figure 7. Time of first intervention. Outliers are marked as red crosses.

The resulting acceleration was analyzed by the following formula [45] and is reported as portions of the gravitational force g (9.81 $\mathrm{m/s^2}$) for better classification (see Figure 9):

$$a_{res} = \sqrt{a^2_{longitudinal} + a^2_{lateral}} \tag{1}$$

Approximately the same resulting acceleration can be found in the experimental and baseline drive in the *free* scenario (*M* = 0.29 (*SD* = 0.12) and *M* = 0.31 (*SD* = 0.12)). In contrast, accelerations in the *occupied* scenario were about two times higher (HMI REC: *M* = 0.61 (*SD* = 0.23) and HMI BL: *M* = 0.62 (*SD* = 0.11)).

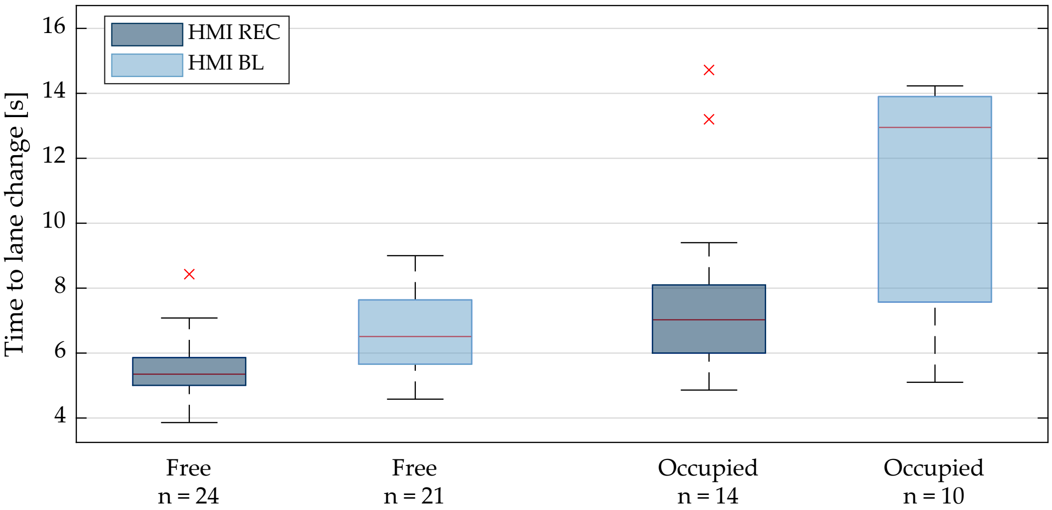

Figure 8. Time to lane change. Outliers are marked as red crosses.

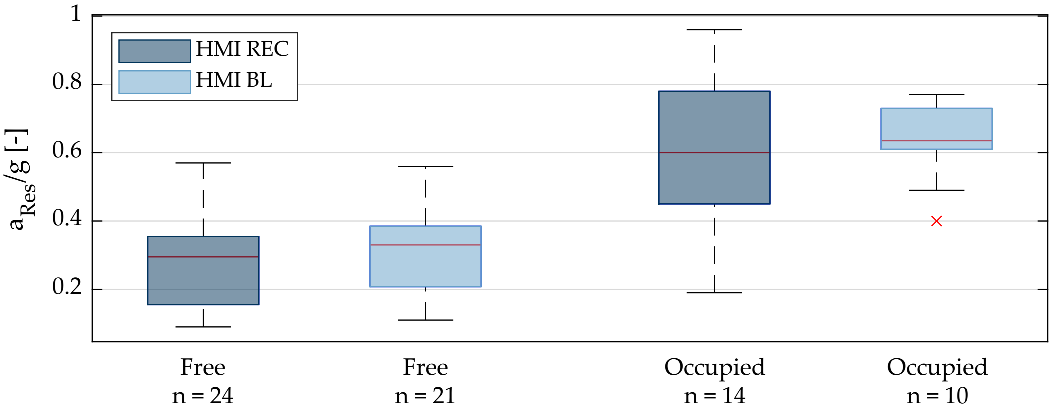

Figure 9. Resulting acceleration as portion of g (9.81 $\mathrm{m/s^2}$). Outliers are marked as red crosses.

Intervening in the transition phase can imply several consequences, especially if other traffic participants are apparent. None of the participants collided with the obstacle in their own lane. Nevertheless, dangerous situations can occur as listed in Table 3. All of these consequences do not have the same weight, e.g., an accident is obviously more harmful than an overshoot, and total numbers have to be put into context. Overshoots were classified as dangerous since they represent poor steering behavior and unintended lane change. Only overtaking maneuvers through the middle lane occurred in the *free* scenario and negative consequences were those maneuvers with overshoots, i.e., ego vehicle entering the far left lane, and those maneuvers starting after the MRM was initiated by the system (see also Figure 6). The latter has an impact on the vehicle dynamics because driver and automation intention are opposed. More negative consequences were apparent with the HMI BL in the *free* scenario than with HMI REC (3 (13.6%) vs. 1 (4.0%)).

Critical interventions in the *occupied* scenario occurred while overtaking from left and right. Even if most participants decided to brake in order to let the traffic in the middle pass and overtake afterwards, one participant during both the baseline and experimental drive maneuvered in between the convoy of vehicles and caused an accident. Overtaking from the right (or through the shoulder lane) happened with both HMIs and more frequently with the HMI REC (see Figure 5). An overshoot in this case meant that the ego vehicle is located on the grass strip next to the highway. In total, the proportion of interventions that led to negative consequences is also higher with HMI BL than with HMI REC during the *occupied* scenario (3 (30.0%) vs. 3 (21.4%)).

Table 3. Consequences of driver intervention and corresponding frequencies during the transition phase.

Scenario	**Consequences of Driver Intervention**	**Frequencies**	
		HMI REC	**HMI BL**
Free	Overtaking from left with overshoot	1 (4.0%)	2 (9.1%)
	Intervention after start of MRM	–	1 (4.5%)
Total		1 (4.0%)	3 (13.6%)
Occupied	Accidents	1 (7.1%)	1 (10.0%)
	Overtaking from right with overshoot	2 (14.3%)	2 (20.0%)
Total		3 (21.4%)	3 (30.0%)

3.3. Subjective Data

The subjective data included two questionnaires related to workload and trust in automation collected after each drive as well as the semi-structured interview at the end of experiment. One participant in the experimental drive and two in the baseline drive were excluded from the subjective data analysis due to the reasons described in Section 2.6. Therefore, excluding missing data for statistical tests resulted in a $n = 33$.

On average, NASA RTLX scores were lower with HMI REC ($M = 22.38$, $SD = 12.59$) than with HMI Baseline ($M = 26.25$, $SD = 15.44$) (see also Figure 10). Given a nominal distribution, a one-tailed paired samples t-test showed that this difference is significant ($t(32) = -1.847$, $p = 0.037$, $d = 0.322$) and consequently, hypothesis 2 is accepted.

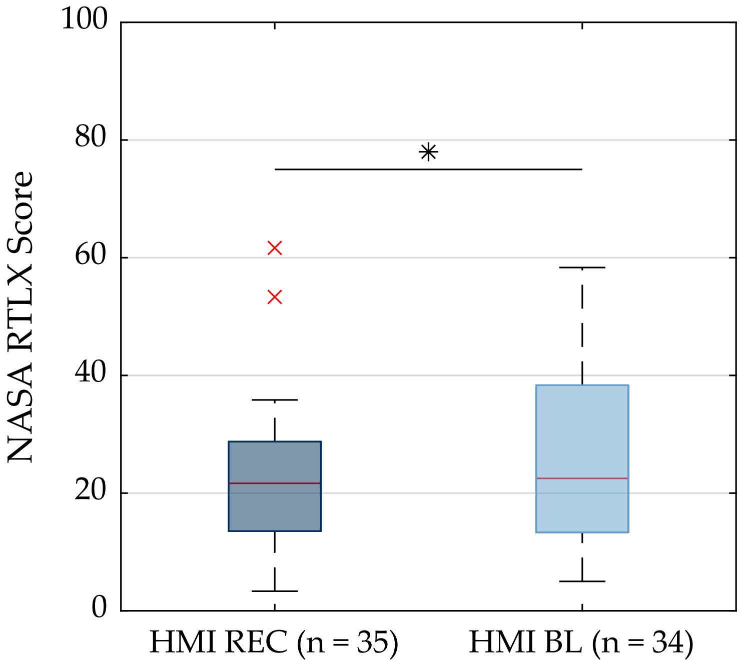

Figure 10. NASA RTLX scores. Outliers are marked as red crosses. The asterisk represents a statistical significant difference ($p < 0.05$).

The TiA questionnaire consists of six subscales that can be used and independently interpreted from each other. As shown in Table 4, the average score was significantly higher with the HMI REC (*Mdn* = 4.00) than HMI BL (*Mdn* = 4.00) in the subscale *Understanding/Predictability* with medium effect size ($z = 1.79$, $p = 0.036$ (one-tailed), $r = 0.312$). Non-significant test results indicate either no difference or a decrease in the scores in the other subscales (see Table 4).

Table 4. Scores of the TiA questionnaire with answers in each subscale ranging from (1) strongly disagree to (5) strongly agree. Wilcoxon Signed Rank Test is abbreviated as WSRT.

	HMI REC			**HMI BL**			**WSRT**	
Subscales of TiA Questionnaire	**M**	**SD**	**Mdn**	**M**	**SD**	**Mdn**	**z**	**p**
Reliability/Competence	3.58	0.52	3.50	3.47	0.52	3.42	1.42	0.078
Understanding/Predictability	4.08	0.60	4.00	3.90	0.69	4.00	1.79	0.036
Familiarity	2.84	1.39	2.50	2.90	1.39	2.50	0.90	0.186
Intention of Developers	4.11	0.79	4.00	4.09	0.75	4.00	−0.55	0.729
Propensity to Trust	2.79	0.63	2.67	2.73	0.68	2.67	0.87	0.194
Trust in Automation	3.79	0.75	4.00	3.90	0.69	4.00	1.21	0.111

One of the purposes of the semi-structured interview at the end was to understand the participants' reasons for and against an intervention during the transition phase. Reasons for an intervention were heterogeneous with the majority (70.3%) stating they disagreed with the MRM strategy, i.e., maneuvering to the right and coming to a standstill. Other reasons were mentioned comparably fewer times as shown in Table 5. In contrast, a more homogeneous distribution can be found with regard to the reasons against an intervention. Nearly half of the stated reasons were that participants trusted in the automation and its ability to solve the situation (48.9%). Furthermore, the lack of time to assess the situation and the engagement in the NDRT together account for 37.8% of the reasons. The desire to experience an MRM (8.9%) and intervention (2.7%) were low. Participants also changed their willingness to intervene if they were unsatisfied with the course of their previous intervention (4.4%).

Table 5. Reasons for and against an intervention during the transition phase. Multiple answers were possible.

	Summarized Reasons	**Frequencies**
For	Disagree with the MRM strategy	26 (70.3%)
	Follow the recommendation	3 (8.1%)
	Trust in own skills	2 (5.4%)
	Spontaneous reaction	2 (5.4%)
	No trust in automation	2 (5.4%)
	Braking due to obstacle	1 (2.7%)
	Desire to experience an intervention	1 (2.7%)
Against	Trust in automation	22 (48.9%)
	Lack of time to assess situation	9 (20.0%)
	Distraction because of NDRT	8 (17.8%)
	Desire to experience an MRM	4 (8.9%)
	Uncertainty because of previous intervention	2 (4.4%)

3.4. Re-Entering into Traffic

If there was no intervention or in the case of a standstill maneuver in the shoulder lane, the re-entry into traffic process was analyzed. During the *free* scenario, two participants decided to overtake the obstacle through the middle or left lane with HMI REC and HMI BL. This number is higher in the *occupied* scenario during the HMI REC, i.e., 10 overtaking maneuvers through the middle lane, as well as the HMI BL drive, i.e., 5 overtaking maneuvers through the middle lane including one overshoot (see Figure 11).

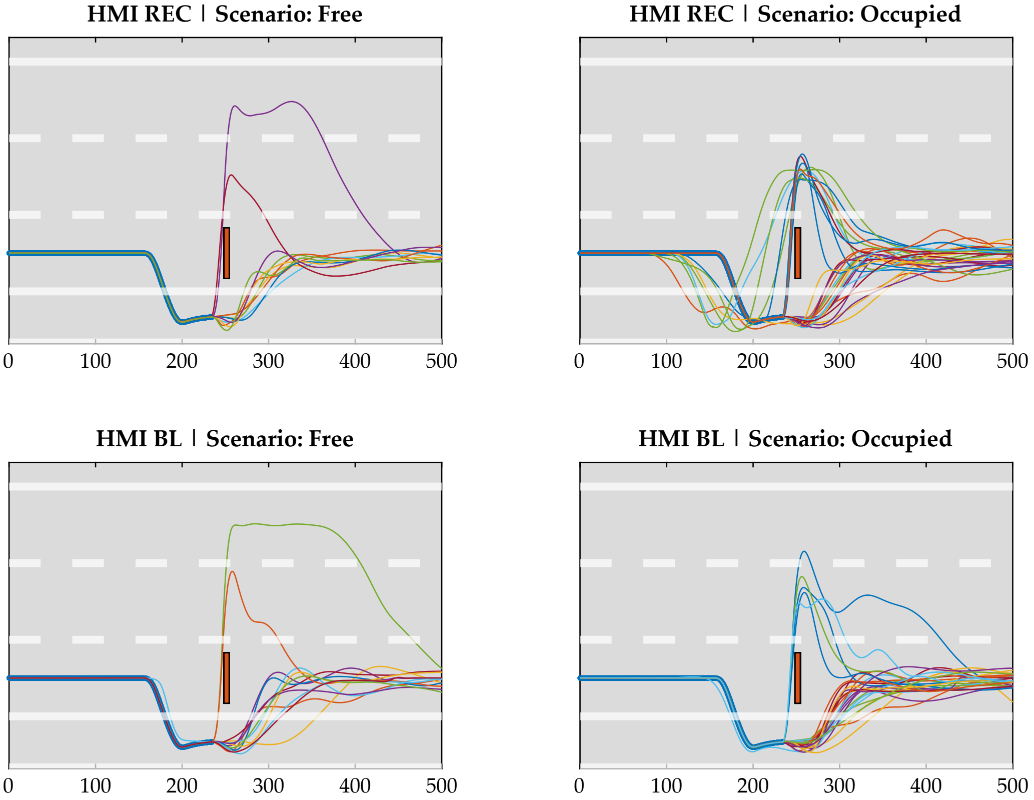

Figure 11. Trajectories of the center of gravity of ego vehicle if there was no intervention or in the case of a standstill maneuver in the shoulder lane. The blue thick line shows the trajectory of the MRM and transition phase starts at 0 m.

4. Discussion

In this experiment, we aimed to reduce the risk of an accident by providing environmental information and action recommendations to the driver during a transition phase with MRMs. To this end, we developed an HMI concept and investigated its effects during two scenarios: one in which participants should easily be able to follow the recommendation (*free*) and one in which participants would find it more difficult (*occupied*). Another objective of the study was to ensure that this concept does not negatively effect driver's workload and trust in automation.

Since an intervention during the transition phase was not mandatory and the MRM would safely bring the vehicle to a standstill on the shoulder lane, the number of interventions was analyzed first. Results show that there is a high proportion of drivers who intervene during both scenarios, with higher numbers in the *free* scenario as compared to the *occupied* scenario. Nevertheless, the goal of an MRM is to ensure a safe transition phase regardless of the scenario and the number of interventions during at least one scenario emphasizes the importance of this investigation: 68.6% with HMI BL and 77.8% with HMI REC. These results can be compared to the "MRM evasive" scenario in the experiment by Karakaya et al. [20]. In that study, the number of interventions for participants who were allowed to intervene was less (46.4%) than during the *free* scenario with both HMI concepts (HMI REC: 69.4%, HMI BL: 62.9%). Even if two different MRM strategies were investigated, the decision to intervene during at least one transition phase was similar (71.4%). According to our analysis, providing environmental information and action recommendations did not influence the decision to intervene. Consequently, the higher intervention rates in this study must be due to other factors, such as transition design, i.e., prolonged time for voluntary takeover from 3 s to 6.5 s, an additional HMI element, i.e., cHUD, absence of a motion platform, etc. The main reason for an intervention as stated during the interview was that participants disagreed with the MRM strategy (70%), similar to the results of [20]. Other reasons for and against an intervention also matched.

Results from [19,20] could be confirmed here again since a maneuver to the left is clearly favored by the participants over one to the right. A standstill maneuver in their own lane was not performed by any participant, but is a proposed MRM found in the literature (see Section 1.1). Even if the middle lane is blocked and a lane change to the left is dangerous, participants had the desire to overtake through that lane by slowing down, sometimes close to a standstill, to let the traffic pass before starting to change the lane. Two participants during the baseline and experimental drive did not wait while slowing down and maneuvered in between the convoy, causing an accident in each case. The positive effect of the HMI REC is a shift in the manner of intervention: more standstill maneuvers in the shoulder lane, less overtaking from the left, and an increase in overtaking from the right. The latter is not necessarily a positive effect since it is against the traffic law in Germany and passengers in the stranded vehicle could be located on the shoulder lane, which in turn was not the case in the simulated scenario.

Recommendations via the HMI were followed by all participants during the *free* scenario. This is not surprising since the maneuver recommended by the system conforms with the one desired by drivers. In the *occupied* scenario, 50% of all intervening participants followed the recommendation. This proportion could increase if there were more experienced transition phases with MRMs, more trust in the automation, or more uncertainty regarding the participant's own takeover. It could also decrease due to the previously stated reasons such as lacking time to assess the situation or significant distraction because of the NDRT. In order to change the willingness to follow the recommendations by the systems, these factors need to be considered. However, none of the participants stated unclear recommendations as a reason for or against an intervention. Thus, the cHUD is a suitable mean to communicate the recommendations of the ADS and changes in the HMI type are not assumed to be a factor for improvement. On the contrary, insufficient communication of the recommendations and intentions of the ADS could lead to higher intervention rates of drivers and consequently induce higher risks.

Analysis of the driving performance of drivers who intervened showed that the time of first intervention was the nearly the same regardless of the scenario or HMI and was on average 4 s after the transition was initiated. Therefore, the first intervention seems to be a reactive action to the MRM announcement. This assumption is supported by the fact that nine participants intervened before the audio message, including the verbal announcement of the MRM, had finished. The analysis of the time to lane change shows the influence of supporting the previous stages of the information processing model via information out of the traffic environment shown in the HMI on the *response selection* stage (see Section 2.2.1): a tendency of a 1 s earlier lane change in the *free* scenario was found due to the HMI REC. Longer times and higher standard deviations in the *occupied* scenario can be explained by the shift of intervention manners through the HMI, i.e., more participants overtaking from the left during the baseline drive. This is analogous to the resulting acceleration that showed no difference between the HMIs in the *free* scenario. Higher acceleration rates are also caused by braking either to gain time for a lane change or to come to a standstill in the shoulder lane. The higher standard deviation with the HMI REC results from a more heterogeneous distribution of intervention manners.

The developed HMI concept yielded a lower subjective workload by the drivers. Moreover, its influence on trust in automation was analyzed with the TiA questionnaire [44]. As stated in hypothesis 3, higher values in each subscale were assumed prior to the experiment. Results showed a significant difference only in the scale concerning understanding and predictability of the system. No difference or a decrease of the scores in the other subscales are feasible due to non-significant results. Therefore, we could only observe a positive influence on one factor of perceived trustworthiness according to the model by Körber [44]. This contributes to increasing trust in automation, and in terms of a holistic enhancement, the other factors have to be considered in future studies.

Risk is formulated as the product of the severity of an harmful event and its probability of occurrence [17]. To answer the research question posed by this study, one of these two factors or both need to be reduced. First of all, the harmful event during the transition phase, especially combined with an MRM, has to be defined. Applied to this context, no harmful event occurs if participants let the system perform its MRM, since we simulated a flawless automation. Here, the only risk occurs after automatically coming to a standstill, i.e., during the process of re-entering into traffic, when drivers decide to overtake the stationary obstacle with an overtaking maneuver through the middle lane. Drivers should be guided after an MRM since a slow overtaking through the shoulder lane is less prone to cause an accident than through the middle lane.

Risk assessment in the case of a driver intervention depends greatly on the definition of the harmful event, i.e., a (1) collision with other traffic participants and/or a (2) dangerous situation. The severity of a collision was assumed to be the same across all possible collisions in the *occupied* scenario. A lower frequency of accidents with the HMI REC (7.1%) as compared to HMI BL (10.0%) correlates with lower probabilities of the occurrence of an accident and thus a reduction of the collision risk. Dangerous situations were overshoots during lane changes and interventions timed after the MRM. Given a similar severity within a situation, again the frequency and therefore the probability of occurrence solely determines the risk level. Lower frequencies of dangerous situations were found with the HMI REC than with the HMI BL within the *free* scenario (4.0% vs. 13.6%) as well as the *occupied* scenario (14.3% vs. 20.0%). Overtaking maneuvers through the middle lane with low velocities, i.e., an average speed of 42 km/h, or through the shoulder lane were also performed by participants in the *occupied* scenario. The former is potentially dangerous for upcoming vehicles with driving at faster velocities and the latter due to potential passengers who left the stranded vehicle. Although this was not the case in our study, it could be added to the dangerous situations and corresponding difference in the frequencies between HMI REC and BL would be higher (42.9% vs. 80.0%). In either case, the risk of a dangerous situation is lower with the developed HMI concept. Consequently, the risk of an accident and a dangerous situation can be reduced by providing environmental information and action recommendations. In addition, trust is positively influenced by increasing the driver's understanding and predictability of the system and subjective workload being reduced.

5. Limitations

The presented study took place in a static driving simulator and results have to be validated in field studies for absolute validity [46]. It can be assumed that the effect of the developed HMI will still be present in real-world driving, which is considered to be relative validity. Even if the inhibition threshold in reality for a driver intervention is higher due to vivid consequences and thus the risk of a poor takeover is more devastating than in the simulation, the intervention rate of approximately 70% in one of two transition phases has to be considered. Steering behavior in a driving simulator combined with the absence of kinesthetic information is different in reality and thus negative consequences of an intervention, e.g., overshoots during lane changes or steering after the start of an MRM, could be mitigated or exacerbated. On the one hand, kinesthetic feedback helps drivers to correct their actions. On the other hand, steering contrary to the MRM could impair the vehicle dynamics in reality. Results must be taken into account under the premise of a highly accurate cHUD that displayed information within the simulation. The brake acceleration rate in this experiment during the MRM was 6 m/s^2 and higher than proposed by the UNECE [16], i.e., 4 m/s^2. Higher deceleration rates could theoretically indicate a greater urgency, but can be excluded in the presented study due to the different perception of accelerations in static driving simulators. Higher rates in simulations can also be found in the literature, e.g., 10 m/s^2 [41].

Author Contributions: Conceptualization, B.K.; methodology, B.K.; software, B.K.; validation, B.K.; formal analysis, B.K.; investigation, B.K.; resources, B.K. and K.B.; data curation, B.K.; writing—original draft preparation, B.K.; writing—review and editing, B.K. and K.B.; visualization, B.K.; supervision, K.B.; project administration, K.B.; funding acquisition, K.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the German Federal Ministry of Education and Research within the scope of the research project CADJapanGermany: HF (grant number 16ES1034K).

Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki, and approved by the Institutional Review Board of the Ethics Commission of the Technical University of Munich (protocol code 506/21 S-KH on 8 August 2021).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to the privacy policy.

Acknowledgments: The authors thank Bilal Aksoy for preparing experiment materials and conducting the study.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

Abbreviations

The following abbreviations are used in this manuscript:

ADS	Automated Driving System
cHUD	Contact Analog Head-Up Display
DDT	Dynamic Driving Task
HMI	Human Machine Interface
MRC	Minimal Risk Condition
MRM	Minimal Risk Maneuver
NDRT	Non-Driving Related Task
ODD	Operational Design Domain
SAE	Society of Automobile Engineers
TiA	Trust in Automation

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2023 IEEE Intelligent Vehicles Symposium (IV) | 979-8-3503-4691-6/23/$31.00 ©2023 IEEE | DOI: 10.1109/IV55152.2023.10186745

Changing the Perspective: Assessing the Controllability of Minimal Risk Maneuvers for Surrounding Traffic Participants

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***Abstract*—A mixed traffic consisting of manual and automated vehicles will be part of reality in the near future. Vehicles of higher automation levels, which will have the ability to perform minimal risk maneuvers, will also participate in this traffic. Previous research in this area has focused on the interaction within the automated vehicle and a change of perspective was therefore carried out in this study. Three different maneuvers were evaluated from two perspectives of the surrounding traffic with regard to their controllability. A new method was used to evaluate the driving performance individually. The results of the driving simulator study with 35 participants show that an MRM in the form of a lane change coupled with a standstill on the shoulder lane is the most controllable. The results are consistent from both investigated perspectives.**

***Index Terms*—minimal risk maneuver, controllability, naturalistic driving study, driver behavior**

I. INTRODUCTION

The development of the automotive industry is increasingly leading to the automation of several parts of the driving task [1], [2]. Especially higher automation levels are gaining more and more interest. Vehicles at these levels of automation and above are able to take over the driving task and only hand it back to the driver under certain conditions. One vehicle function is increasingly coming into focus, so that even this transition can be spared for the driver or is intended to provide more safety: minimal risk maneuver (MRM). With the help of these maneuvers, so-called minimal risk conditions are to be achieved, which are supposed to entail a lower risk than the initial state. The literature mainly suggests the standstill, which should take place either on the shoulder lane or in the own lane, if possible [3], [4]. However, intermediate steps are also feasible to achieve this state [5]. Ultimately, however, the driver is always required to take over the driving task from a point in time. Even during the transition phase, driver takeovers should be allowed and result in different maneuvers being performed than those intended by the automation. Karakaya et al. investigated this interaction and discovered two main findings for this study: first, there is a high desire of drivers to intervene in MRMs and take over the driving task, and second, by doing so, they may increase the risk of an accident. The maneuver that drivers then perform is mainly an overtaking maneuver from the left, which is in line with the road traffic regulations in Germany [6], [7]. There is still a long way to go before the introduction is complete and traffic consists mainly of automated vehicles. Hence, there will be a transitional period with mixed traffic, i.e. manual and (partially) automated vehicles. So far, research in this area has mainly focused on the driver in the automated vehicle (AV) and its interaction with the system. In order to assess the maneuvers holistically, the question arises how mixed traffic reacts to it and whether it poses new risks. Therefore, in this study, we changed the perspective (see Fig. 1) to answer the following research question: Which MRMs are controllable to surrounding traffic? In order to objectively answer the controllability question, a new method was developed in this

Fig. 1. Investigated perspective in this study. A stranded vehicle causes an MRM of the AV that drives in front of the ego vehicle. The picture was extracted from the simulation software SILAB.

This research was funded by the German Federal Ministry of Education and Research within the scope of the research project CADJapanGermany: HF (grant number 16ES1034K).

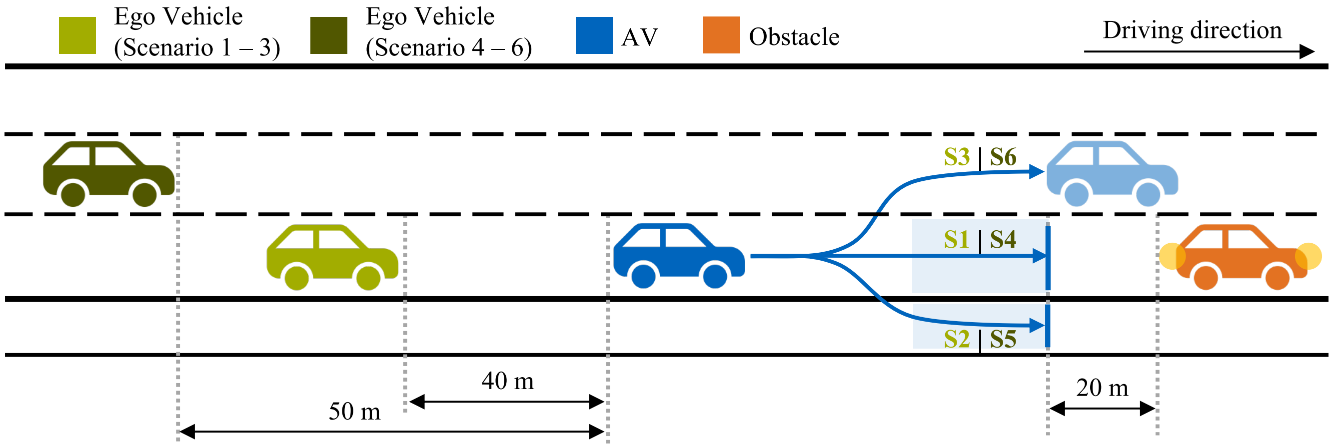

Fig. 2. Schematic illustration of the implemented scenarios in the experimental drive. S1 to S6 represents Scenarios 1 to 6.

study based on the ISO 26262 definition: "ability to avoid a specified harm or damage through the timely reactions of the persons involved, possibly with support from external measures" [8, p. 6]. In our case, there is no external measure and it is not the aim to perform a hazard assessment based on the ASIL levels. The classification of controllability was only used as an inspiration and led to the individual scale for the driving performance of a participant. The timely reaction was measured in terms of the resulting acceleration values, whereas the hazard was a stranded vehicle.

II. METHOD

A. *Experimental Design and Dependent Variables*

A within-subject design with the scenario as the independent variable was used in this study. This was required due to the novel approach to evaluate the driver's driving performance individually. Every participant experienced 6 scenarios, which differed in the MRM of the vehicle ahead (see Fig. 2). The sequence of scenarios was permuted. The dependent variables were:

- Performed maneuver as a reaction to the MRM in front.
- Reaction time: braking (greater than 0) or steering input (difference greater than 2°) by the driver. Acceleration as a reaction was excluded from the analysis since differentiating between a conscious change in the gas pedal position as a reaction to the situation rather than regulating the vehicle's velocity is difficult.
- Enhanced Time To Collision (ETTC) as defined in [9]:

$$ETTC = \frac{\left[-\Delta v - \sqrt{\Delta v^2 - 2 * \Delta a * x_C}\right]}{\Delta a} \qquad (1)$$

  Differences in speed and accelerations are calculated as target vehicle minus subject vehicle. The distance between both vehicles is x_C.
- Accelerations resulting from the maneuver performed.
- Criticality of intervention: causing dangerous situations or accidents.

The most suitable metric to evaluate a driving performance individually are the longitudinal and lateral accelerations since they represent the outcomes from the participant's performed maneuver. They combine the results of gas, brake, and steering wheel input as well as their timings. Therefore, each participant completed a benchmark drive before the experiment and their acceleration data was collected. The data included lateral and longitudinal accelerations during two representative scenarios, i.e. *uncritical* and *critical*, and each scenario was repeated three times. The mean values represent the threshold for a (un-)critical acceleration. The values in between were equally distributed and resulted in four categories, in which the accelerations from the experimental drive can be assigned afterwards: *uncritical*, *rather uncritical*, *rather critical*, and *critical* (see Fig. 3). After analyzing the data in MATLAB (TheMathWorks Inc.) and Excel (Microsoft Inc.), statistical tests were conducted in JASP (JASP Team) with a significance level of α = .05.

B. *Scenarios*

1) Benchmark Drive: Participants drove on a two-lane highway without any traffic other than the obstacle and were instructed to conduct a braking maneuver until standstill and an evasive maneuver. Both maneuvers had to be performed during an *uncritical* and *critical* situation, which had different Time To Collision (TTC) values with regards to the obstacle. Furthermore, the obstacle was visible and the start of scenario was announced via a computer generated voice message during the *uncritical* scenario. In contrast, the obstacle suddenly

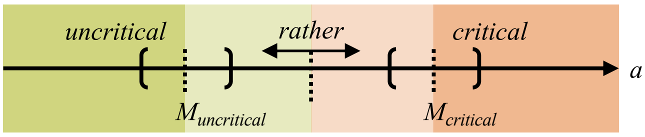

Fig. 3. Individual categories for accelerations derived from the benchmark drives.

appeared during the *critical* scenario. The implemented TTC values were 8.5 s (*uncritical*) and 3.5 s (*critical*) during the braking maneuver and 7.5 s (*uncritical*) and 2.5 s (*critical*) during the evasive maneuver. Each scenario was repeated three times and with an ego-vehicle speed of 80 km/h and 100 km/h.

2) Experimental Drive: The AV performed three different MRMs, i.e. a standstill on the own lane, a standstill on the shoulder lane, and an overtaking maneuver from the left. The first two MRMs are common proposals from taxonomies [3], regulatories [4], and other literature [5]. The third MRM was derived from [7] and represents a maneuver performed by drivers when intervening an MRM. While the AV was always located on the right lane and performed its MRMs, the driver behavior was investigated from two different perspectives: ego vehicle located on the (a) right (Scenarios 1 to 3) and (b) middle lane (Scenarios 4 to 6). The speed limit during the scenarios on the right lane was 80 km/h and 100 km/h during the middle lane scenarios. The AV had a deceleration speed of -4 m/s^2 according to [4] and a distance of 40 m (speed limit 80 km/h) and 50 m (speed limit 100 km/h) to the ego vehicle. The distance to the obstacle was 20 m when the AV came to a standstill. Some measures were taken to ensure that participants experience the scenarios, e.g. traffic signs signalizing a ban of overtaking until the AV performs its MRM (Scenarios 1 to 3) and a convoy traveling behind the AV to enforce a driving on the middle lane (Scenarios 4 to 6). To ensure that all participants had comparable scenarios, the following conditions had to be fulfilled:

- Lane: ego vehicle on the right lane (Scenario 1 to 3) or middle lane (Scenario 4 to 6).
- Speed: more than 70 km/h (Scenario 1 to 3) or 90 km/h (Scenario 4 to 6).
- Distance: less than 45.5 m (Scenario 1 to 3).
- Steering: less than 2° steering angle change to check a lane-changing attempt due to anticipation.

C. Procedure

After welcoming the participants, documents pertaining to the safety instructions, study information, and consent form were handed out and signed by all parties. A pseudonymization code was used for data collection. The participants were instructed that they would drive in a mixed road traffic with automated vehicles. MRMs and the scenarios in the experimental drive were not explained. They were also told that AVs could encounter system limits, which disengages the automation. At first, a training drive was completed followed by the benchmark and experimental drives. Finally, the participants filled out a questionnaire on each experienced scenario and were compensated with 30 euros.

D. Participants

A valid driver's license and a minimum age of 18 were required to participate in this study. The sample consisted of 35 participants with 27 male and 8 female participants. The average age was 25.40 years (SD = 5.87, Min = 19, Max = 53).

E. Apparatus

A static driving simulator with five 55-inch ultra HD screens and a 180° field of view was used for the experiment. The rear view was positioned on top of the middle screen, and the side mirrors were implemented as two additional displays. On the bottom of the middle screen a Head-Up Display (HUD) was implemented that showed the vehicle's current speed and traffic signs. Behind the steering wheel was a freely programmable instrument cluster, and audio speakers were mounted around the mockup. The Würzburg Institute of Traffic Sciences' (WIVW) SILAB 6.0 program was employed for the driving simulation. A GoPro HERO 4 mounted on a tripod behind the driver's seat video recorded the experiment.

III. RESULTS

A. Benchmark Drive

The reference value for a (un-)critical longitudinal acceleration was derived from the standstill maneuver during the respective scenario from the benchmark drives. The value for lateral acceleration was analogously derived from the evasive maneuvers. None of the participants had an overlap of their individual mean value, i.e. the critical mean values were always lower than the uncritical ones. The overall distribution can be found in Fig. 4 and Tab. I. Paired samples t-tests were conducted to test the validity of criticality during the situations and showed significant differences with large effect sizes between all *uncritical* and *critical* scenarios (see Tab. II). Normality distributions were given for all tests and were analyzed via the Saphiro-Wilk tests.

B. Experimental Drive

The number of valid data sets of the scenarios is different from each other due to the requirements as described in Section II-B2.

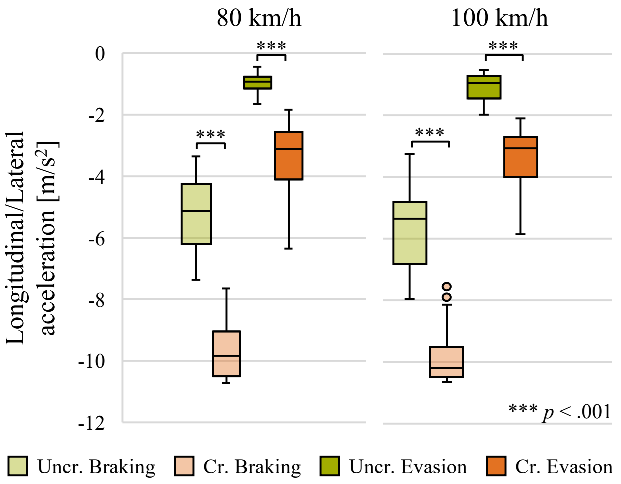

Fig. 4. Distributions of the longitudinal (derived from the standstill maneuvers) and lateral accelerations (derived from the evasive maneuvers) during the critical (*Cr.*) and uncritical (*Uncr.*) scenarios (n = 35).

TABLE I
REFERENCE VALUES DURING BENCHMARK DRIVE

Scenario		Longitudinal acceleration [m/s^2]		Lateral acceleration [m/s^2]	
Speed	***Criticality***	***M***	***SD***	***M***	***SD***
80 km/h	Uncritical	-5.18	1.10	-0.99	0.31
	Critical	-9.64	0.95	-3.36	1.11
100 km/h	Uncritical	-5.70	1.16	-1.05	0.41
	Critical	-9.84	0.90	-3.37	0.89

TABLE II
STATISTICAL TESTS FOR THE BENCHMARK DRIVE

Scenario		Paired samples t-test			
Speed	***Type***[a]	***t***	***df***	***p***	***Cohen's d***
80 km/h	Standstill maneuver	18.7	34	<.001	3.17
	Evasive maneuver	14.4	34	<.001	2.44
100 km/h	Standstill maneuver	18.9	34	<.001	3.20
	Evasive maneuver	16.1	34	<.001	2.73

[a] Difference always between *uncritical* and *critical.*

TABLE III
PERFORMED MANEUVER IN SCENARIOS S1 TO S6

Manner of maneuver	Scenarios					
	S1	***S2***	***S3***	***S4***	***S5***	***S6***
Standstill on the own lane	5	2	0	–	–	–
Lane change to the left	29	28	31	9	1	16
Keeping the lane	–	–	–	26	34	19

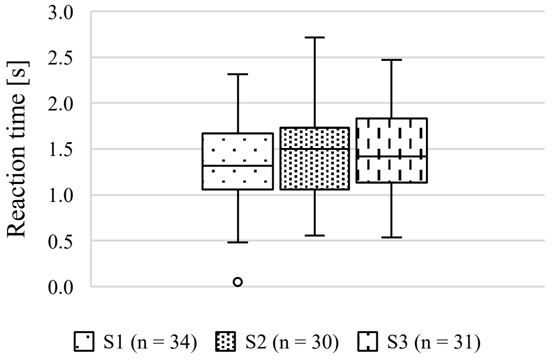

Fig. 5. Distributions of the reaction times during Scenarios 1 to 3.

1) Performed Maneuver: The participants reacted differently during the scenarios and their performed maneuvers are given in Tab. III. The majority of participants chose to overtake the AV from the left during Scenarios 1 to 3, i.e. the AV in front of the ego vehicle performs an MRM. However, more drivers chose to brake until standstill when the AV in front also came to a standstill (S1). This amount is reduced if the AV comes to a standstill on the shoulder lane (S2). None of the participants chose coming to a standstill if the AV overtook the obstacle from the left and all of them followed the AV to the middle lane (S3). During the scenarios from the other perspective, i.e. the vehicle on the right next lane performs an MRM (S4 - S6), a driver reaction was not mandatory and consequently resulted in a majority of drivers who continued driving on their lane. Results show that participants conduct proactively a lane change to the left in order to clear the lane for the AV. This was most often done when the AV actually performed a lane change to the middle lane (S6), followed by the scenario in which the AV came to a standstill on its own lane (S4). Only one participant performed this maneuver when the AV came to a standstill on the shoulder lane (S5).

2) Reaction Time and ETTC: The mean as well as the standard deviation of the reaction times of participants during Scenario 1 (*M* = 1.36, *SD* = 0.50), Scenario 2 (*M* = 1.42, *SD* = 0.52), and Scenario 3 (*M* = 1.49, *SD* = 0.55) were comparatively equal (see Fig. 5). A Friedman test was conducted due to a violation of normality distribution and showed no significant difference between the scenarios ($\chi^2(2) = 1.19$, $p = .553$).

Two participants were additionally excluded from ETTC analysis, i.e. one each in S1 and S2, because they brushed the standstill vehicle while overtaking. These were not counted as accidents since the simulation software does not show the ego vehicle's contour and this could only be seen in the data afterwards. The mean ETTC in Scenario 1 was lower (*M* = 1.28, *SD* = 0.77) than in Scenario 2 (*M* = 1.76, *SD* = 0.51) and Scenario 3 (*M* = 1.61, *SD* = 0.79) (see Fig. 6). A Friedman test as a result of not normally distributed data showed a significant difference between the scenarios ($\chi^2(2) = 8.62$, $p = .013$). A Conover's post hoc comparison with Bonferroni correction showed a significant difference between Scenario 1 and 2 ($p = .023$). No significant differences were found between Scenarios 1 and 3 ($p = .093$) and Scenarios 2 and 3 ($p > .99$).

Reaction times and ETTC were not analyzed for Scenarios 4 to 6 since no reaction was required in order to solve the situation.

3) Rating of Driving Performance Individually: The individual performance of all participants during each scenario in the experimental drive was allocated to one category derived from its benchmark drive (see Tab. IV). The number of *Critical* and *Rather critical* accelerations was considered to evaluate the scenarios. The results show that participants reacted most critically when the MRM is a standstill on the own lane (S1),

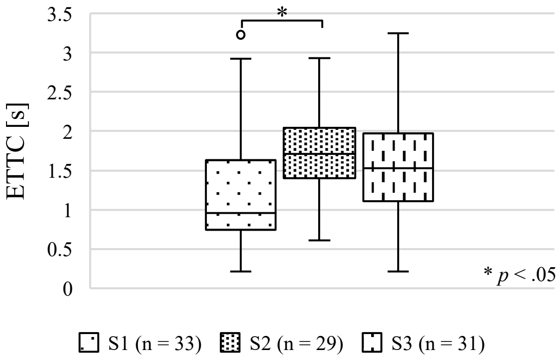

Fig. 6. Distributions of ETTC during Scenarios 1 to 3.

TABLE IV
Results of the Allocation of Individual Performance

Categories	Scenarios					
	S1	*S2*	*S3*	*S4*	*S5*	*S6*
Uncritical	1	1	0	25	34	11
Rather uncritical	12	18	17	9	1	15
Rather critical	17	9	10	1	0	9
Critical	4	2	4	0	0	0

followed by an overtaking from the left (S3), and a standstill on the shoulder lane (S2), if the AV in front of the ego vehicle performs the MRM. The overall criticality of driver behavior in the other perspective, i.e. S4 to S6, is lower. However, rating the scenarios among each other shows that the overtaking maneuver from the left (S6) caused the most critical reactions followed by the standstill maneuver of the AV on the own lane (S4) and the standstill maneuver on the shoulder lane (S5).

4) Negative Consequences: Negative consequences were defined as an accident – either with the AV, the obstacle, or the surrounding traffic – an ETTC value less than 1.6 s [10, p. 1165], or an overshoot during an overtaking maneuver. Overshoots are unintended lane changes for a short period of time. The results in Tab. V show that one participant during Scenario 4 had an accident while changing the lane to the left. The vehicle collided with approaching traffic from behind. The highest number of critical situations due to low ETTC values can be found in Scenario 1, followed by Scenario 3 and Scenario 2. One overshoot while changing lanes per Scenario 1 to 3 was recorded.

5) Subjective Data: The participants were asked in the final questionnaire whether they perceived a scenario as dangerous. Pictures of the scenarios were shown beforehand and remembering the situation was required to answer the question, leading to different sizes of n per scenario (see Tab. VI). Results show that, for the first perspective, Scenario 3 was rated as dangerous by the most participants, followed by Scenario 2 and 1. The results are similar for the second perspective, where the most participants rated Scenario 6 as dangerous, followed by Scenario 4 and 5.

IV. Discussion

In order to answer the research question of which MRM is controllable to surrounding traffic and whether some are more easily controllable than others, various metrics were used. Thereby, the goal of this study was to make this assessment based on objectively measurable variables. The discussion addresses both perspectives in detail in order to provide an overall assessment at the end.

The first perspective is the one where the AV is located in front of the ego vehicle (S1 to S3). The first metric to consider regarding the controllability is the number of accidents. Two accidents occurred when the subjects attempted to pass the stranded vehicle from standstill. Since their own vehicle's contour was not displayed in the simulation, drivers could not estimate the exact distance during low speed maneuvering. This resulted in collisions being detected in the data analysis but they were not visible in the simulation. These two cases were not counted for the described reasons, which is why there was no collision with another road user overall. In all other categories, the scenario in which the AV comes to a stop in its own lane (S1) performs worse than in the other scenarios: the number of dangerous ETTC values is highest (total: 24), the individual driving performance has the most "critical" and "rather critical" ratings (numbers combined: 21) and the ETTC is significantly lower than in Scenario 2. The latter could be due to the fact that the AV comes to a standstill in its own lane and therefore has different distances and accelerations than when it makes a lane change. However, this difference should then have affected the differences between Scenario 1 and 3. In Scenario 3, where the AV swerves to the left, dangerous ETTC values occurred less frequently (total: 16) and the number of "critical" and "rather critical" ratings regarding driving performance were also lower (numbers combined: 14). In both categories, therefore, Scenario 2, in which the AV swerved to the right onto the hard shoulder and stopped, performed best. The number of dangerous ETTC values here was 10 and individual driving performance was rated as "critical" or "rather critical" a total of 11 times. Differences in reaction times between scenarios were not found.

In the second perspective, the AV is located in the lane to one's right (S4 to S6). There was a total of one accident (2.9%) in Scenario 4 in which the AV came to a stop in its own lane. This is interesting in the sense that there was no need for action from the participant's point of view, especially since the AV does not cross one's own lane. Being considerate of the AV, the participant swerved into the left lane and collided with approaching traffic. The evaluation of the driving performance shows that values from the "critical" category did not occur in any of the scenarios. Therefore, the scenarios do not pose a major challenge to the drivers. Nevertheless, accelerations of the category "rather critical" occurred more often in Scenario 6 than in the others (total: 9). Scenario 5 performed better with only one subject in this category. The scenario in which the

TABLE V
Negative Consequences of Driver Behavior

Criticality	Scenarios					
	S1	*S2*	*S3*	*S4*	*S5*	*S6*
Accidents	0	0	0	1	0	0
Dangerous ETTC (<1.6 s)	24	10	16	–	–	–
Overtaking from the left with overshoot	1	1	1	0	0	0

TABLE VI
Scenarios Perceived as Dangerous

Perceived as dangerous	Scenarios					
	S1	*S2*	*S3*	*S4*	*S5*	*S6*
Yes	31%	14%	52%	15%	3%	53%
No	69%	86%	48%	85%	97%	47%
n	35	35	33	33	33	34

vehicle swerves onto the shoulder lane (S4) performs best here (total: 0). The subjective assessment of the test subjects shows a similar picture. However, since the accident is not negligible and is weighted higher than the rest of the metrics, Scenario 4 is rated as the most difficult to control, followed by Scenario 6 and 5.

In summary, the results from both perspectives are consistent. If the AV comes to a standstill in its own lane, it is the hardest for the surrounding traffic to cope with. An evasive maneuver of the AV to the left, which in this case represented a driver intervention in an MRM, is more controllable for the manual driver. Clearly, however, changing the lane and coming to a standstill on the shoulder lane performed best on every metric. Drivers appear to be less confused as a result and can focus better on the traffic events.

V. LIMITATIONS

To generate the scenarios, the AV's speed was linked to the participant's one. Depending on the speed while approaching the scenario, this can sometimes lead to a slow deceleration of the AV until it reaches the same speed. An overtaking ban was introduced in the area so that participants do not take the opportunity to overtake. This could appear unnatural to subjects and result in a learning effect. The sample did not have a homogenous distribution of gender and age. The majority of participants were young male students that were recruited from the university.

VI. CONCLUSION

In this study, MRMs were investigated from the perspectives of the surrounding traffic in a driving simulator experiment. A new approach was used to individually assess the driving performance of the participants. The results show that an MRM in the form of a lane change coupled with a standstill on the shoulder lane is desirable regarding the controllability of the manual driver. The evasive maneuver to the left, which represented an intervention by the AV's passenger, performed worse in each metric. However, the subjects had the greatest difficulties when the AV stopped in its own lane, which also led to one accident.

ACKNOWLEDGMENT

The authors thank Konstantin Allgayer for preparing the experimental materials and conducting the study.

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