Assessment of safety and related societal benefits

Deliverable D4.1 – WP4 – PU

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Tejas Chandran – Autoliv

Report Author(s):	Chandran, T., Jan, H., Morando, A. (Autoliv), Sweden Yuan, Y., Farah, H., (Delft University of Technology), The Netherlands Kreußlein, M. (TU Chemnitz), Germany Fiorentino, A. (FCA Italy), Italy van Birgelen, T.M. (NLR) The Netherlands

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Legal Disclaimer

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List of Abbreviations

ACC	Adaptive Cruise Control
ADAS	Advanced Driver Assistance Systems
ADS	Automated Driving System
AEB	Autonomous Emergency Braking
BM	Block Maxima
CCDF	Complementary Cumulative Distribution Function
CM	Continuous Mediation (automation level)
DRT	Driver Reaction Time
ECDF	Empirical Cumulative Distribution Function
EVT	Extreme Value Theory
GDP	Gross domestic product
GEV	Generalized Extreme Values
HIC	High Income Country
HMI	Human Machine Interface
KPI	Key Performance Indicators
LMIC	Low- And Middle-Income Country
MCMC	Markov Chain Monte Carlo
NUTS	No-U-Turn-Sampler
ODD	Operational Design Domain
OECD	Organisation for Economic Co-operation and Development
PA	Pilot Assist
PDF	Probability Density Function
PI	Percentile Interval
QALYs	Quality Adjusted Life Years
RL	Return Level
RP	Return Period
SAE	Society of Automotive Engineers
SB	Driver Standby (automation level)
TI	Technology Integration prototype vehicle

TOC	Transition of Control
TOR	Take Over Request
TTAF	Time To Automation Fitness
TTAU	Time To Automation Unfitness
TTC	Time To Collision
TTDC	Time To Driver Comfort
TTDD	Time To Driver Discomfort
TTDF	Time To Driver Fitness
TTDU	Time To Driver Unfitness
TtS	Time To Sleep (automation level)
UC	Use Case
VOSL	Value Of Statistical Life
WHO	World Health Organization
WP	Work Package
WTP	Willingness-To-Pay

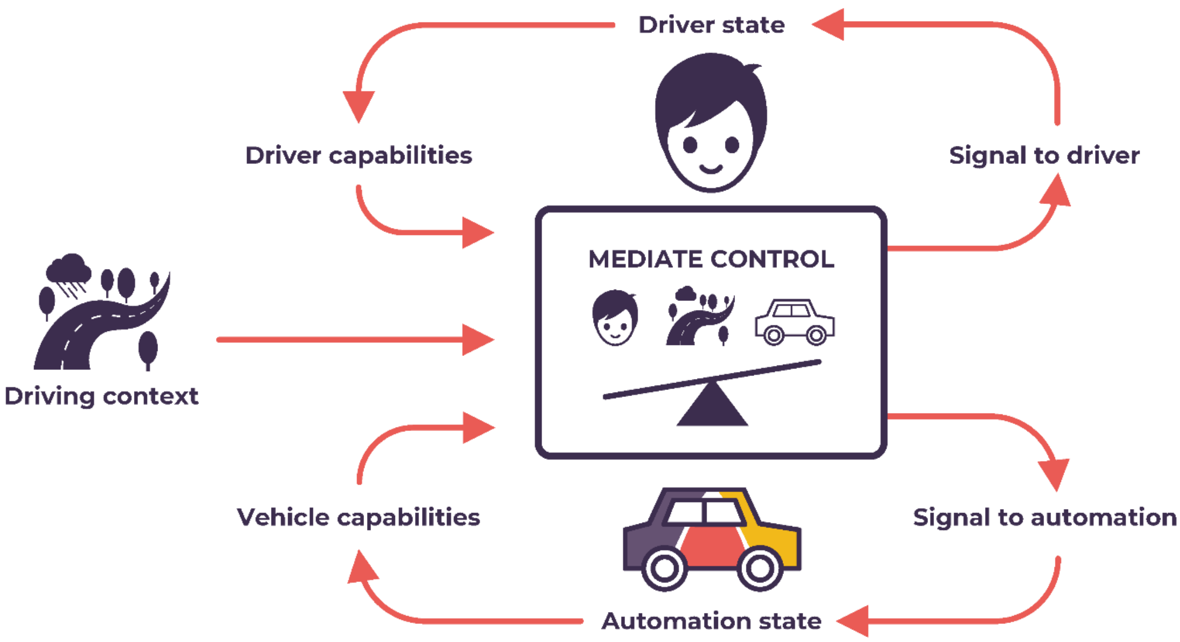
About MEDIATOR

MEDIATOR, a 4-year project coordinated by SWOV Institute for Road Safety Research, has come to an end after four years of hard work. The project has been carried out by a consortium of highly qualified research and industry experts, representing a balanced mix of top universities and research organisations as well as several OEMs and suppliers.

The consortium, supported by an international Industrial Advisory Board and a Scientific Advisory Board, represented all transport modes, maximising input from, and transferring results to aviation, maritime and rail (with mode-specific adaptations).

Vision

Automated transport technology is developing rapidly for all transport modes, with huge safety potential. The transition to full automation, however, brings new risks, such as mode confusion, overreliance, reduced situational awareness and misuse. The driving task changes to a more supervisory role, reducing the task load and potentially leading to degraded human performance. Similarly, the automated system may not (yet) function in all situations.



The Mediator system will constantly weigh driving context, driver state and vehicle automation status, while personalising its technology to the drivers' general competence, characteristics, and preferences.

The MEDIATOR project aimed to develop an in-vehicle system, the Mediator system, that intelligently assesses the strengths and weaknesses of both the driver and the automation and mediates between them, while also taking into account the driving context. It assists the timely take-over between driver and automation and vice versa, based on who is fittest to drive. This Mediator system optimises the safety potential of vehicle automation during the transition to full

(level 5) automation. It would reduce risks, such as those caused by driver fatigue or inattention, or on the automation side by imperfect automated driving technology. MEDIATOR has facilitated market exploitation by actively involving the automotive industry during the development process.

To accomplish the development of this support system MEDIATOR integrated and enhanced existing knowledge of human factors and HMI, taking advantage of the expertise in other transport modes (aviation, rail and maritime). It further developed and adapted available technologies for real-time data collection, storage and analysis and incorporated the latest artificial intelligence techniques. MEDIATOR has developed working prototypes, and validated the system in a number of studies, including computer simulation, virtual reality, driving simulator and on-road studies.

With MEDIATOR we further paved the way towards safe and reliable future vehicle automation that takes into account who is most fit to drive: the human or the system.

https://mediatorproject.eu/

Executive summary

The Mediator system is a driving assistance system that provides recommendations for the safest driving mode in a specific driving context. In this report, we evaluate the safety potential of the Mediator system, which is a facilitator for realizing the safety potential of both automated and manual driving. It can make manual driving safer by counteracting and mitigating distraction and drowsiness.

Five studies are included in this MEDIATOR report, which assess the safety and societal benefits of utilizing the Mediator system in real-life car-following or rear-end crash traffic scenario.

The first study adresses Estimated frequency of collisions.

The initial study conducted an evaluation of the benefits of Adaptive Cruise Control (ACC) in comparison to manual driving using a statistical model known as Extreme Value Theory (EVT). Surrogate metrics, such as Brake Threat Number (BTN), were used to evaluate conflicts between the two driving modes. BTN was found to be the appropriate metric to compare automated and manual driving mode, this is mainly due to that other metric system (such as TTC & THW) does not take the breaking behaviour and performance into account. The study applied the EVT method to estimate the frequency of rear-end collisions with and without ACC (or pilot assist's longitudinal control). The results showed that the use of ACC significantly reduces the occurrence of rear-end collisions in comparison to manual driving. However, it is important to note that defensive driving may still be a safer option than relying solely on ACC. The Mediator, which does not directly affect safety, can recommend the safer driving mode based on driving context and driver characteristics such as driving style, distraction, and fatigue. This study highlights that automation may not always be the superior option.

Second study is about Observed safety performance indicators.

The second study presents an analysis of the safety performance of the Mediator system using data collected from the TI in-vehicle prototype field test in Sweden. The analysis uses several key safety performance indicators, including average attention and distraction values, time to collision (TTC), driver reaction time (DRT), and speed volatility, in combination with the related automation status of drive scenarios and the availability of the Mediator system. The results show that there is a marginal but still significant difference in the average attention and distraction values when the Mediator system is available versus unavailable. Drivers were more often not looking ahead while driving when the Mediator system was available, which could be expected as drivers trust the Mediator system. However, since the difference is marginal, it not likely to impose higher risks compared to driving without the Mediator system.

The analysis also shows that during pilot assist driving, TTC is larger, which indicates a potential positive impact on safety when driving with pilot assist control and Mediator. Moreover, it is expected that the Mediator system would encourage drivers to drive with Pilot-Assist when it is available and within its operation conditions, increasing automation usage.

Third study is about Estimated societal benefits.

The third study is about estimating the societal benefits of using the Mediator system. Mediator is designed to ensure the correct usage of automated driving systems, increase predictability, and prevent crashes caused by impaired driving states. The system is not mandatory, and the driver decides if the system is activated during a trip. Assuming best-case scenario of an 88% acceptance rate, (based on the simulator study where 88% of participants indicated that they would use the system), the study estimates that Mediator could have prevented 17,738 and 13,012 extra-urban rear-end collisions in Germany in 2019 and 2020, respectively, with an assumption of 50% effectiveness rate.

The conclusion from this study is that the financial benefits of the system depend on its market penetration and the standard unit cost of a crash. The financial benefit ranges from 0.003% to 0.26% of the gross domestic product (GDP) depending on the country. The societal benefits in terms of avoided road injuries also range from around 0.01% to 0.2% of the GDP. The Mediator system also has the potential to reduce crashes caused by factors such as distraction, fatigue, discomfort, and environmental conditions, although this has not yet been calculated. Overall, the Mediator system has the potential to significantly reduce crash rates and associated costs in the future.

Fourth study is about Estimated performance in traffic flow.

The fifth study evaluates the impact of the Mediator system on traffic congestion by analysing the behaviours induced by the Mediator equipped vehicle on surrounding vehicles. The study uses real-world driving data from the TI-prototype vehicle to simulate the motion behaviour of the Mediator-equipped vehicle in a virtual environment. The study further evaluates how surrounding drivers of different types affect car-following behaviours in this simulated environment.

Four scenarios were designed, involving two types of drivers and two sub-routes. The study employs several congestion related performance indicators to evaluate the impact of the system, including maximum deceleration, standard deviation of speed, and aggregated speed volatility. The results show that the Mediator system in the moderately invasive version outperforms the others in all scenarios and driving behaviours of surrounding vehicles. The usage of the pilot assist system is found to reduce the likelihood of traffic accidents, prevent sudden stops, and starts, improve traffic flow, dampen stop-and-go waves, stabilize flow, and expand the portion of smooth driving. The Mediator system in this configuration can improve traffic stability and congestion by providing real-time information and promoting safe driving behaviour.

Fifth Study is about Safety assessment of Mediator system using expertise from aviation domain.

The focus of the fifth study were various scenarios of safety assessment of the Mediator system, such as the case of Mediator initiating an automation take-over in case of severe distraction or incapacitation, and the case of Mediator advising an automation take-over in case of fatigue, distinguishing for SAE levels of driving automation 0 to 5.

In both cases, the results anticipate a safety benefit for using Mediator system (fewer accidents due to fatigue, distraction, and incapacitation). However, certain conditions must be met for this benefit to occur, such as the availability and activation of the Mediator's driver monitoring system, the availability of the driving automation, and the vehicle being within the Operational Design Domain (which increases with higher levels of driving automation). As the level of driving automation increases, the ODD becomes larger, and the safety benefit becomes larger.

In conclusion, the Mediator system has a significant potential safety benefit. The conclusions are derived from the five studies, which analyze the safety and societal benefits of utilizing the Mediator system in real-life car-following or rear-end crash traffic scenarios. The studies include an estimated frequency of collision, observed safety performance indicators, estimated societal benefits, estimated performance in traffic flow, and safety assessment of Mediator system using expertise from aviation domain. The Mediator system has potential safety benefits, especially when combined with the pilot-assist system, and it can recommend the safer driving mode depending on driving context and driver characteristics such as driving style, distraction, and fatigue. However, certain conditions must be met for the safety benefit to occur, such as the availability and activation of the Mediator's driver monitoring system, the availability of the driving automation, and the vehicle being within the Operational Design Domain (ODD)

1. Introduction

In recent years, there has been considerable progress towards the realization of automated driving. Nevertheless, 1.35 million lives are still lost to traffic crashes annually and several millions more are injured[1]. This has a substantial toll on the society through the loss of production time, human suffering, and property damage. An important driving force for highly automated vehicles is that they are expected to curb these alarming numbers of fatalities and injuries. But as we have learnt over the years from other transportation domains such as aviation and from recent high profile fatal crashes involving misuse or failure of SAE Level 2 driving assistance systems, there are still important questions to be answered – Is automated driving and driving assistance systems safe? How does society gain from these systems? What data do we need to assess their safety?

The MEDIATOR project approaches automated driving in a unique way, by developing a system that can choose whether the human or automated system controls the vehicle for a given context using a variety of input variables. This means that, under ideal operation, the system tries to ensure that it will not be in a situation where both the human driver and the automation are unfit for the driving task. The Mediator system further tries to reduce mode confusion for the driver through the MEDIATOR levels of automation. The strength of this strategy lies in that even when in manual driving, the Mediator system supports the driver to be safer by mitigating fatigue and distraction (D1.1, D1.4, and D3.4)[2].

One of the focus areas in current automation state-of-art is motorway driving (for example, EU funded project L3Pilot[3]) and regulations such as UN R157[4]. These systems primarily use Adaptive Cruise Control (ACC) for longitudinal control component with Lane Keep Assist for lateral control component. In this deliverable, we evaluate the safety and societal benefits of the Mediator system by selecting a real-world traffic scenario which is already available in the market – car-following driving on motorways (with and without ACC) where rear-end crashes are a prevalent type of crash. According to EU statistics, motorways accounts for an average 9% of all car occupant fatalities with Europe's worst performing country as high as 18%[5] [6]. Motorway driving is typically characterized by high speeds and monotonous driving – an important factor for distraction and fatigue. Further, the results in D3.4 further support our scenario selection where automated driving systems were deemed most useful to drivers in motorway driving context, and they did not trust automation in city driving and on rural roads.

The distance to other traffic participants (such as Time to Collision, Time Headway) are important variables for identifying likelihood or closeness to collision (D1.2). These variables are common for both human and automated system performance. In terms of driver state, D1.2 identified two main KPIs – distraction and fatigue – which Mediator mitigates and reduces in both manual and automated driving. However, in D3.4, the effect of distraction was found to vary between participants where distraction increased for some participants while it decreased for others. One of the reasons for this variation was the HMI was not fluid enough in the current testing state. Even though the Mediator's driver state assessment component was accurate in detecting driver distraction, it appears that the Mediator HMI

[1] World Health Organization. (2018). Global status report on road safety 2018.

[2] See note on the pages 2-3 for an explanation of MEDIATOR deliverable terminology.

[3] L3Pilot Consortium (2021) Deliverable 1.7 Final Project Results, retrieved from: https://l3pilot.eu/downloads

[4] UN ECE (2020). Proposal for a new UN Regulation on uniform provisions concerning the approval of vehicles with regards to Automated Lane Keeping System. ECE/TRANS/WP.29/2020/81. Retrieved from https://unece.org/fileadmin/DAM/trans/doc/2020/wp29/ECE-TRANS-WP29-2020-081e.pdf

[5] European Commission (2021) Facts and Figures Car occupants. European Road Safety Observatory. Brussels, European Commission, Directorate General for Transport

[6] European Commission (2021) Facts and Figures Motorways. European Road Safety Observatory. Brussels, European Commission, Directorate General for Transport

produces an unintended distraction. As a result, on an average, the effect was not significant and didn't point towards any specific different direction. This makes it difficult to generalize the results as it is unclear how to translate the effect on distraction to a larger pool of participants or prolonged use. Our summary (Chapter 4) relays this finding of a marginal improvement. These results are based on a short portion (ca. 7 minutes) of the continuous mediation real-world driving (1.12% of drive with baseline HMI and 0.67% with Mediator HMI). This accounts for a fraction of the data that is needed for reliably generalizing the results of Mediator's performance in counteracting distraction on EU roads. As a result, this aspect of Mediator is not quantified further in Chapter 5 and onwards, though its potential is commended. The field experiments found that there was no observed effect on driver fatigue between when using Mediator system compared to baseline driving. As a result, fatigue was considered out of scope in the quantification of benefit presented here.

The Mediator system affects the strategic and tactical levels of driving[7] by anticipating and transferring control between human and automation in a timely manner. This means proving a direct safety benefit of control level interventions or actions for Mediator is not realistic (such as those provided by Advanced Emergency Braking, or Forward Collision Warning would avoid a rear-end crash scenario). We assume that in the chosen context, the Mediator system maintains safety by anticipating and advising the driver to hand over control to the vehicle or vice versa. In MEDIATOR D3.2, it was found that the Mediator decision logic tested in the TI-prototype vehicle could determine a safe situation (where either driver or automation is fit to drive) in 99.9% of the tested scenarios. Thus, the analysis in this report we assumed both the Mediator system and the automation perform their respective tasks as intended, as they would in an ideal scenario.

The objectives of this deliverable were to assess both the safety and societal benefits of the Mediator system. These two objectives were addressed through five studies – three addressing safety benefits and two addressing societal benefits – each of which were carried out by different organization and documented as individual chapters.

1. Since Mediator is a system that facilitates between driving modes based on which one is the safest for a given context, we first asked how safe are the driving modes? How can we use real-world driving data to quantify and compare the crash risks between automated driving and manual driving? (See Chapter 2 Estimated frequency of collisions)
2. The next question that emerged was if automated driving is safer in a certain context, could Mediator encourage or promote the use of automation? How does Mediator address key human factors challenges such as distraction in both driving modes? (See Chapter 3 Observed safety performance indicators)
3. When a crash occurs, it is not only an impact to those involved in the crash. It carries a substantial toll on society and the economy. If Mediator can achieve the safety potential in 1. and 2., then how does this translate into societal gains? Why should policymakers invest into adopting Mediator at large-scales on European and world roads? (See Chapter 4 Estimated societal benefits)
4. When a new system like Mediator is widely adopted into traffic, it could cause disruptions in traffic which can have negative impacts on safety and society. For example, if the system causes vehicles to move at slow speeds, it could lead to risky behaviour among other road users and result in time lost in traffic congestion. Therefore, we investigated whether the implementation of Mediator has such unintended consequences on the surrounding traffic. (See Chapter 5 Estimated performance in traffic flow)
5. Over the years, road safety has collaborated with other fields, including aviation, to address human factors challenges related to automation. Although aviation operates in a different context and time scale, there are many similarities that road safety can adopt. Consequently, to complement the traditional road safety studies, we enlisted an aviation safety expert to evaluate

[7] Michon, J. A. (1985). A critical view of driver behavior models: what do we know, what should we do?. *Human behavior and traffic safety*, 485-524.

the safety potential of Mediator using a similar approach as one would to assessing automation in aviation. (See Chapter 6 Safety assessment of Mediator system using expertise from aviation domain and Chapter 7 Effort required to develop a safe driver monitoring system .

We have primarily used the on-road data from the TI in-vehicle prototype from the Sweden trials in the studies presented in Chapter 3 and 5 as these studies relied on real-world interactions with other traffic participants. Chapter 4 uses both results from TI in-vehicle prototype and the driving simulator trials in Chemnitz, Germany (D3.3).

In this report, we refer to several other MEDIATOR deliverables and reports. For the sake of clarity, they are as follows:

D1.1: Christoph, M., Cleij, D., Ahlström, C., Bakker, B., Beggiato, M., Borowsky, A., …Van Nes, C.N (2019). Mediating between human driver and automation: state-of-the art and knowledge gaps. D1.1 of the H2020 project MEDIATOR

D1.2: Borowsky, A., Oron-Gilad, T., Chasidim, H., Ahlström, C., Karlsson J.G., Bakker, B., … Christoph, M. (2020). Behavioural Markers for Degraded Human Performance. Deliverable D1.2 of the H2020 project MEDIATOR.

D1.3: Mano, D., Berger, N., Larsson, A., Brännström, M., Knauss, A., Toffetti, A., … Christoph, M. (2021). Quantified Markers for Degraded Automation Performance, Deliverable D1.3 of the H2020 project MEDIATOR.

D1.4: Cleij, D., Bakker, B., Borowsky, A., Christoph, M., Fiorentino, A., van Grondelle, E., Mano, D, van Nes, N. (2020). Mediator System and Functional Requirements, Deliverable D1.4 of the H2020 project MEDIATOR

D3.1: Beggiato, M., Rauh, N., Li, Y., Borowsky, A., Toffetti, A., Ahlström, C., … Christoph, M. (2021). Guidelines for design and methodological approach of the evaluation studies, Deliverable D3.1 of the H2020 project MEDIATOR.

D3.2: Athmer, C., Spaan, M.T.J., Li, Y., Liu, Y., Bakker, B. (2022). Simulation of Decision Making in the Mediator System, Deliverable D3.2 of the H2020 project MEDIATOR.

D3.3: Borowsky, A., Schwarz-Chassidim, H., Hollander, C., Rauh, N., Enhuber, S., Oron-Gilad, T., Beggiato, M. (2023). Results of the MEDIATOR driving simulator evaluation studies, Deliverable D3.3 of the H2020 project MEDIATOR

D3.4: Fiorentino, A., Ahlström C., S. Andersson, Toffetti A., (2023). On-road evaluations of the vehicle-integrated Mediator system, Deliverable D3.4 of the H2020 project MEDIATOR.

D3.5: Rauh, N., Springer-Teumer, S., Spaan, M., Borowsky, A., Fiorentino, A., Ahlström, C., Thalya, P. (2023). Integration of evaluation results from the MEDIATOR studies, Deliverable D3.5 of the H2020 project MEDIATOR.

2. Estimated frequency of collisions

2.1. Introduction

The task of driving can be structured in three levels (Michon, 1985): *strategical* (planning), *tactical* (manoeuvring), and *operational* (control). For the most part, Mediator operates at the strategic level (e.g., planning driving mode changes during the route), but the instantaneous manoeuvring and control of the vehicle (e.g., to maintain a safe distance from other objects) is the responsibility of the driver or of an automated system (e.g., adaptive cruise control [ACC]). To assess the overall safety benefit of Mediator, we need to estimate the safety benefit of the driving modes that are mediated. Then, Mediator can be designed to recommend the safest driving mode based on the current traffic circumstances.

One of the driving modes that Mediator can recommend is driving with ACC. ACC is a common advanced driver assistance system (ADAS) that increases comfort by reducing the effort of continuous longitudinal control. ACC can also reduce the exposure to critical lead-vehicle situations (e.g., rear-ends) by keeping a fixed headway to the vehicle in front. Without ACC, drivers may often tailgate so that they would not have enough time to evade a conflict (General Motors Corporation Research and Development Center, 2005, Chapter 8; Malta et al., 2012, Chapter 4). While ACC may decrease the exposure to safety critical situations overall, its direct safety benefit (e.g., reduction in rear-end crash risk)—net of the human factors associated with it—are still unclear. For example, ACC is considered relatively safer than manual control because it reduces the frequency of short (less than 1 s) headways (General Motors Corporation Research and Development Center, 2005, Chapter 8; Malta et al., 2012, Chapter 4), but the absolute collision risk has not been quantified.

There is little work on estimating the real-world safety benefit of systems like ACC. Traditionally, safety benefit analyses have used crash databases to assess safety under manual control (e.g., Otte et al., 2003). Because crashes are rare and (in some way) unique—they are the result of specific driver-vehicle-system dependencies (Coughlin et al., 2011), multiple failure mechanisms (Singh, 2015), and co-occurrence of unexpected events (Victor et al., 2015)—it would take too long to collect a representative sample and design countermeasures. Most safety assessment analyses have also focused on autonomous emergency interventions (e.g., autonomous emergency braking [AEB]) and not on sustained automation (e.g., convenience systems like ACC). In fact, crash databases may be insufficient to investigate the effects of current (and newer) ADASs because the market penetration of this systems is still low and even more so because their operation during a crash is not reported anyway (Otte et al., 2003).

As more consumer vehicles are equipped with ADAS (and more sophisticated forms of automation), we need a method to rapidly assess if they are safe based on their technological risks and benefits (Blumenthal et al., 2020), and improve them accordingly (Åsljung et al., 2017). There are multiple alternatives to using crash data. The most common approach is to use near-crashes (or other crash surrogates) from naturalistic driving data (e.g., Dingus et al., 2006) in combination with simulation (e.g., Kusano et al., 2022; Olleja et al., 2022). Near-crashes are convenient as they are more frequent than crashes, but many debate on their generalizability (Dozza, 2020; Tarko, 2012). In this chapter, instead, we used Extreme Value Theory (EVT; Coles, 2001). EVT is a way to extrapolate extreme, rare events (crashes) from a set of observations of a process under regime (normal driving). This approach does not require direct observation of conflicts because it relies on regular, normal driving data. EVT could quantify the safety benefit of ADASs as they get deployed and accelerate their development using much shorter observation periods.

Multiple studies have applied EVT to estimate the collision risk under human control (e.g., Åsljung et al., 2017; Farah & Azevedo, 2017; Orsini et al., 2020, 2021; Songchitruksa & Tarko, 2006; Tarko, 2012) and a few investigated highly automated driving (e.g., Kamel et al., 2022). In this chapter, we aimed at comparing human control to ACC (the most common automated driving features in consumer vehicles that Mediator could leverage) in terms of rear-end crash frequency. Rear-ends are the most common type of conflict; ACC is the most common automated features installed in consumer vehicles that could prevent them.

2.2. Methods

2.2.1. Data source

We did not receive the data from the on-road experiments in MEDIATOR in time for this analysis. As an alternative, data was drawn from OpenACC (Anesiadou et al., 2020; Makridis et al., 2021). OpenACC is an open-access dataset to benchmark the performance of ACC installed in high-end consumer vehicles under normal operation. The data was collected over multiple test-track or open-road tests. Data such as speed, acceleration, and range were recorded from the CAN bus and additional sensors. The dataset was stored at 10 Hz.

From OpenACC, we selected the data from the test-track experiment at AstaZero in Sweden. It was the only experiment that included a human control baseline, which was necessary to assess the relative safety benefit of driving with or without support of automation. The experiment consisted of a platoon of five vehicles; the first vehicle in the platoon drove in a traffic-free rural road and occasionally perturbed the platoon by setting a different ACC target speed. Across trials, the following vehicles were the same, but they changed their relative order in the platoon. There was no other traffic in the test-track. Participants were professional drivers.

In all trials but one the ACC's headway was set at the lowest (about 1.2 s); we discarded the single trial that had the ACC headway set to high (above 2 s) for consistency. While the headway setting may sound aggressive, users generally prefer a short time gap to reduce cut-ins (General Motors Corporation Research and Development Center, 2005, Chapter 4). We also kept only those driving segments where the minimum speed of the whole platoon was more than 15 km/h for at least 10 s to include only steady-state (under regime) driving. Finally, the platoon was broken down into independent pairs of vehicles (e.g., the 2nd and 3rd vehicle in the platoon became the leader and follower vehicle, respectively) because we were interested in understanding rear-end crash scenarios and not the effects on the whole platoon. This meant that we assumed that drivers would not anticipate the lead-vehicle actions by looking further ahead in the platoon. Also, we did not study ripple (string) effects from the behaviour of the following vehicle to the vehicles behind. Overall, the amount of data we retained corresponded to about 895 km.

2.2.2. Threat measure

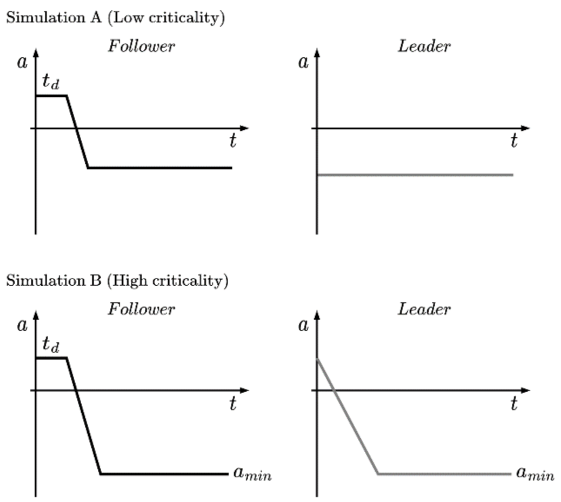


Figure 2-1. Brake profile for the leader and follower vehicle in the two simulated scenario. (Top; Simulation A) The leader maintains the current acceleration. (Bottom; Simulation B) The leader starts a sudden emergency manoeuvre (t_d = 0).

Table 2-1. Brake system's parameters. The deceleration rate j and the maximum capacity a_{min} where kept constant across driving modes as we assumed they are independent of any assistive system and only a property of the vehicle design.

Parameter	Driving mode	Value	Reference
t_d	Manual	1.15 s	UNECE (2022, p. 30)
	ACC	0.1 s	Brännström et al. (2008, p. 104)
j	Manual	-12.9 m / s^3	UNECE (2022, p. 30)
	ACC	-12.9 m / s^3	UNECE (2022, p. 30)
a_{min}	Manual	-7.74 m / s^2	UNECE (2022, p. 30)
	ACC	-7.74 m / s_2	UNECE (2022, p. 30)

We used the brake threat number (BTN; Brannstrom et al., 2008) as a surrogate measure for lead vehicle conflicts. BTN quantifies the brake effort needed to avoid a collision, by comparing the minimum required acceleration to avoid a collision (a_{min_req}) and the minimum acceleration (maximum deceleration) that the brake system is capable of (a_{min}):

$$BTN = a_{min\ req} / a_{min} \qquad (2\text{-}1)$$

with BTN in the (0, ∞) domain. When BTN is greater than 1, then the collision cannot be avoided as it exceeds the brake capacity of the vehicle. BTN depends on braking behaviour and performance—an improvement over the classic time to collision (TTC; Åsljung et al., 2016).

We used a simplified brake profile. First, braking is applied after a delay t_d (e.g., bottom left graph in Figure 2-1). Then, the acceleration decreases linearly with rate *j*. Finally, the braking capacity saturates when it reaches a_{min} (Brannstrom et al., 2008). Specific ACC implementations and brake system characteristics of the vehicles in OpenACC are not in the public domain. Therefore, we used reference values from current regulations or previous studies (Table 2-1). We assumed that ACC would have a high brake authority and we did not include an AEB system.

We computed BTN in two simulated scenarios (Figure 2-1). *Simulation A* is a low-critical scenario that involves a lead vehicle that maintains its current acceleration (top panel in Figure 2-1). *Simulation B* is a high-critical scenario that involves a sudden emergency braking by the lead vehicle (bottom panel in Figure 2-1).

BTN has a convenient closed-form solution only when the lead vehicle is assumed to maintain its current acceleration (Brannstrom et al., 2008), or if both lead and follower vehicle will keep constant acceleration (Åsljung et al., 2017). In this study, instead, we computed BTN as the solution to an optimization problem. This is more computationally demanding, but it allows both vehicles to have any (continuous or piecewise) brake profile (details are in the Appendix A). We computed BTN for all vehicles in the platoon at every second given the current kinematic state of the vehicles from the data (we down sampled the data to 1 Hz to reduce computational cost). Then, we ran a counterfactual simulation at each timestamp: W*hat would happen if the vehicle in front would maintain the current acceleration (simulation A) or start an emergency braking (simulation B)?* The time horizon was set to 30 s, to accommodate events of less criticality. BTN numerically close to 0 were excluded as it means that the simulation did not involve a lead vehicle conflict that required braking at all.

2.2.3. Extreme values analysis

The results from simulation A and B were analysed in two different ways. We used EVT on the data from Simulation A to estimate the probability of a rear-end crash in normal driving situations. We assumed that normal car-following is a set of circumstances that has a non-zero probability of ending up in a conflict so that when the process is repeated enough times it may result in a crash. The assumption is that the process is stationary, smooth, and meaningful to explain rear-end crashes (Coles, 2001, Chapter 1). These are strong assumptions, and some crashes may violate them. Therefore, we used the data from Simulation B to complement the EVT analysis. Simulation B was used to compute the proportion of rear-end crashes that are a result of an exceptional lead-vehicle situation (e.g., a lead vehicle slamming on the brakes suddenly)—a situation that break the stability of the prevailing car-following process.

2.2.3.1. Block maxima

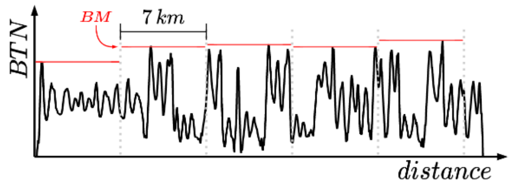


Figure 2-2. Example of block maxima in a timeseries. The timeseries is chunked into blocks of fixed length. Within each block, the max value (BM, marked in red) is extracted. Blocks shorter than the 75% of the desired length were discarded. This likely happens for the last block.

We chunked the BTN timeseries from simulation A into 7 km-long blocks. Then, in each block, we extracted the maximum BTN value (i.e., the block maxima [BM]). The block length was chosen to minimize temporal dependency (Coles, 2001, Chapter 5) and retain the most data (Figure 2-2). On average, trials were about 21 km long, so this resulted in about 3 BM for each vehicle in each trial. Blocks shorter than 75% of the desired block length (something that happens at the very end of the trial) were discarded.

2.2.3.2. Statistical model

BM were aggregated and grouped according to the driving mode (ACC vs. human control). In general, the probability distribution of BM is a Generalized Extreme Values (GEV) distribution regardless of the distribution of the population (Coles, 2001, Chapter 3). The GEV combines the Gumbel, Fréchet, and Weibull families to describe different tail behaviours (bounded or not). Because BTN exists in the domain (0, ∞), we decided to use the Weibull distribution directly, instead of fitting a more general (but complex) class of families. The Weibull distribution has two parameters (mean μ and shape $\alpha > 0$) and formula (Bürkner, 2022)

$$f(y) = \alpha/s\ (y/s)^{\alpha-1} \exp(-(y/s)^{\alpha}) \quad (2\text{-}2)$$
$$\text{where} \quad s = \mu / \Gamma(1 + 1/\alpha).$$

To estimate when a crash may occur in the future (i.e., BTN > 1), we need to estimate when the model predicts BM > 1 from the Weibull distribution that best mimics the observations (Coles, 2001, Chapter 3). To infer the parameters of the distribution for each driving mode, we specified a distributional Bayesian regression model (Bürkner, 2021). In Wilkinsons notation (Wilkinson & Rogers, 1973), the model is

$$BM_i \sim \text{Weibull}(\mu, \alpha) \quad (2\text{-}3)$$
$$\text{where} \quad \mu = \beta_{\mu\ driver[i]}$$
$$\alpha = \beta_{\alpha\ driver[i]}$$

where *driver[i]* is the driver {0: Human; 1: ACC} associated with each data point BM_i. We used the index-variable approach so to assign a unique intercept to each parameter for the specific driving condition (Human, ACC). In this way we can assign priors to each category independently (McElreath, 2019, Chapter 5). We set vague (but regularizing) priors to prevent divergences

$$\mu \sim \text{Student-t}(\mu = 0, \sigma = 2, df = 3) \quad (2\text{-}4)$$
$$\alpha \sim \text{Student-t}(\mu = 0, \sigma = 1, df = 3)$$

Data analysis was done with R (v. 4.2.1; R Core Team, 2022) and the package brms (v. 2.18.0; Bürkner, 2016). We sampled 15 Markov Chain Monte Carlo (MCMC) with the No-U-Turn-Sampler (NUTS; Hoffman & Gelman, 2014) without thinning, and this resulted in post-warmup 45k samples. The MCMC chains (i.e., posterior distribution) carry all the information used for statistical inference.

The goodness of fit for each model was assessed by comparing the posterior predictive distribution against the empirical data (posterior predictive check; Gabry et al., 2017). We used three types of plots, which present the outcome of the statistical modelling at different level of details. The first type compares the modelled Weibull's PDF with the normalized histogram of the data. The second type compares the complementary cumulative distribution function (CCDF) to the complementary empirical CDF of the data (1 – ECDF). Given an ordered sample of BM, $BM_1 \leq \ldots \leq BM_i \leq \ldots BM_m$, the $ECDF_i$ is (Coles, 2001, p. 36)

$$ECDF_i = i / (m + 1) \quad (2\text{-}5)$$

The third plot is the return plot (Coles, 2001, Chapter 3). The return plot can be used to check the model against the empirical observations, but it is also the traditional way of interpreting the outcome of an EVT analysis. The return plot shows the return levels (RL) against return periods (RP, often in the log scale). That is, it shows the value that is likely to be exceeded on average once in that return period (Coles, 2001, Chapter 3). The empirical RL_i is the observed BM_i while the empirical RP_i is calculated as

$$RP_i = 1 / (1 - ECDF_i) \quad (2\text{-}6)$$
$$RL_i = BM_i$$

The estimated RP_i from the model is computed for a range of probabilities of return $p_i \in (0, 1)$, while the RL_i is computed from the complementary of the inverse cumulative distribution function ($1\text{-}CDF_i$) of the Weibull distribution

$$RP_i = 1 / p_i \quad (2\text{-}7)$$
$$RL_i = 1 / CDF_i^{-1}(1\text{-}BM_i)$$

In other words: for the empirical returns we know RL, but we need to calculate the associated RP. Instead, we know RP for the modelled returns, but we need to calculate the associated RL.

Any descriptive statistics of the posterior distribution was derived from the MCMC chains. For convenience, the marginal probability distribution of a parameter/metric was summarized by the median and by the 89% percentile interval (PI; McElreath, 2019, Chapter 3).

2.3. Results

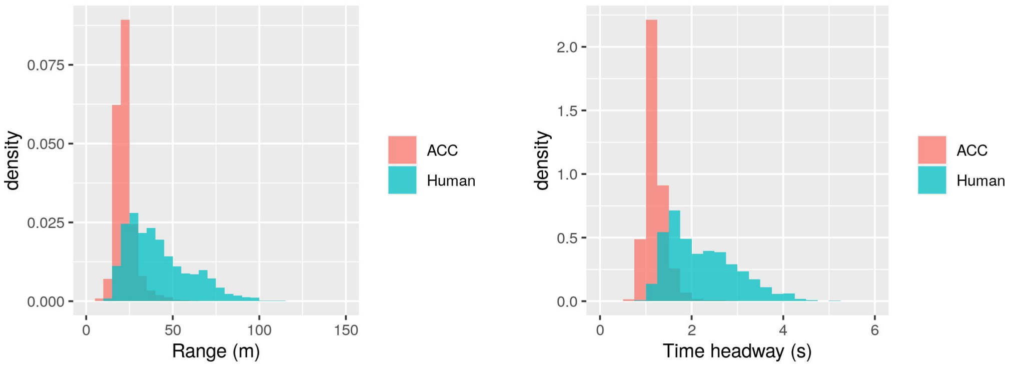


Figure 2-3. Aggregated distribution for range and time headway for all vehicles in the platoon.

Table 2-2. Aggregated descriptive statistics for range and time headway (THW) for all vehicle in the platoon.

Metric	Driving mode	Median	25^{th} – 75^{th} percentile
Range (m)	Manual	38.1	27.5 – 53.2
	ACC	21.3	18.9 – 24.1
THW (s)	Manual	2.08	1.60 – 2.71
	ACC	1.17	1.07 – 1.30

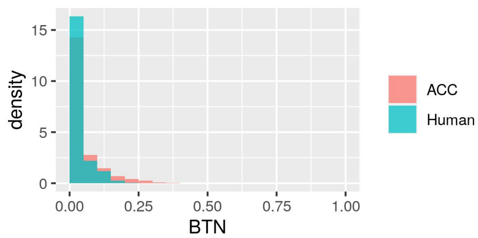


Figure 2-4. Distribution of brake threat number (BTN) in the low-criticality scenario (simulation A) aggregated according to driving mode.

Table 2-3. Summary of inferred parameters (median and 89% percentile interval [PI]) of the Weibull distribution.

Parameter	Driving mode	Median	89% PI
μ	ACC	0.22	0.20 – 0.24
	Manual	0.14	0.13 – 0.16
α	ACC	2.37	2.06 – 2.71
	Manual	2.91	2.14 – 3.79

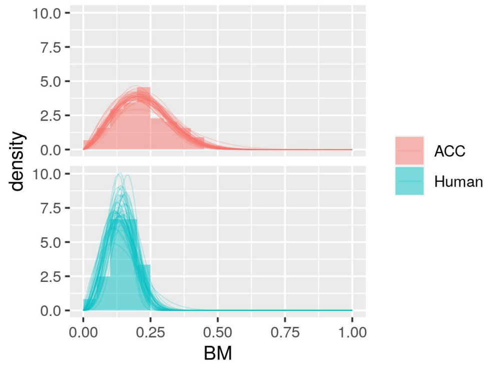


Figure 2-5. Posterior predictive check. The plot consists of a sample of plausible probability densities of the Weibull distribution from the model overlayed to the observed block maxima (BM) histogram. The density estimates are consistent with the histogram of the data.

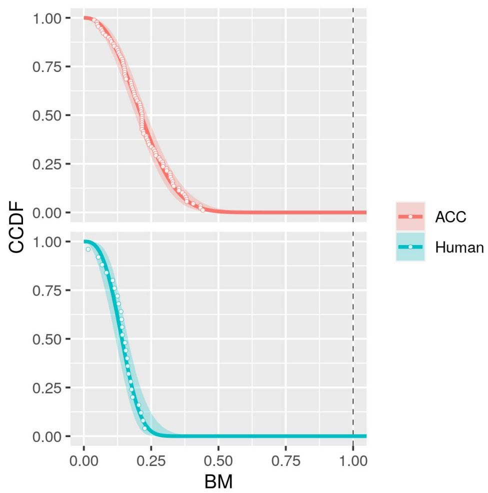


Figure 2-6. Probability of observing a specific brake threat number in the future. The plot shows the complementary of the cumulative distribution function (CCDF) for the model and the observed block maxima (BM) as circles. The expected CCDF for the model is displayed as solid line. Instead, the belt displays the uncertainty in the estimation. The vertical dashed line indicates the critical value for the brake threat number above which a collision is not avoidable. The model agrees with the observations.

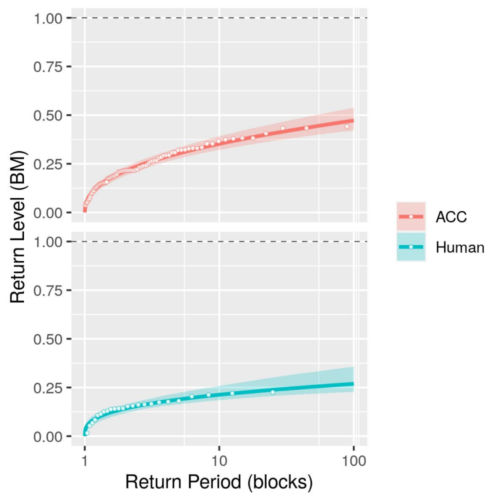


Figure 2-7. Return plot. The plot shows the estimated waiting time (return period) before a block maxima (BM) value (return value) is observed. The expected return from the model is displayed as a solid line. The belt displays the uncertainty in the estimation. The circles are the empirical returns. The dashed horizontal line indicates the critical value for the brake threat number above which a collision is not avoidable. The model agrees with the observations.

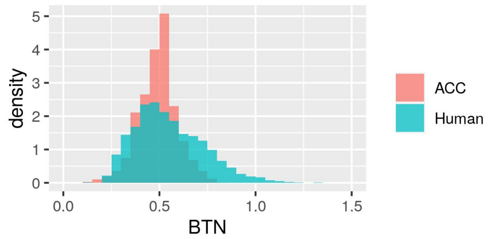


Figure 2-8. Distribution of brake threat number (BTN) in the high-criticality scenario (simulation B) aggregated according to driving mode.

In general, ACC maintained a much shorter headway to the lead vehicle compared to manual driving (Table 2-2; Figure 2-3). The distributions of BTN from simulation A have similar shape, but the one for ACC has a slightly higher mean (ACC = 0.02; Human: 0.01) and longer tail (95% percentile ACC = 0.10; 95% percentile Human = 0.05). No BTN from simulation A was greater than 1, regardless of the driving mode (Figure 2-4).

As no crash occurred in the simulated low-critical scenario (simulation A), we used the Weibull model to estimate if (and when) a crash may occur. The model provided a set of parameters for the Weibull distribution (Table 2-3) that best mimicked the observed BM for each driving mode (Figure 2-5, Figure 2-6, and Figure 2-7). This means that the model, by being a plausible representation of the empirical data, could be used for extrapolation. There was a tendency to higher BM under ACC compared to human control, but the probability of BTN > 1 was essentially zero in both driving modes (Figure 2-6). The inverse of the probability for BTN > 1 is the RP. Based on this, the model suggests that we may expect a crash under normal operation of ACC in 4.79 x 10^{15} km, with the lower bound of PI at 4.1 x 10^{11}. Figure 2-7 shows the RP up to the 100^{th} block (7 x 100 = 700 km) and it shows that the returns started to plateau quickly.

The results from EVT suggest that ACC is associated with relatively greater BTN than under manual control. Taken this result alone, it means that ACC is associated with a higher crash probability (i.e., the inverse of number of blocks) than human control. Specifically, the model suggests that we may expect a crash during normal car-following under manual control in 9.12 x 10^{92} km (lower PI = 3.1 x 10^{26}). Instead, if an emergency arose (e.g., a lead-vehicle suddenly slamming on the brakes; Simulation B), ACC would avoid most (if not all) collisions (Figure 2-8). Both distributions for BTN from Simulation B were centred around 0.5 but the distribution for human control had a longer and thicker tail (Figure 2-8). In case of a highly critical scenario that requires a prompt evasive action, 2% of the simulations for human control resulted in a crash, while no crash occurred under ACC.

2.4. Discussion

Is ACC safe? In general, yes. The results from both simulations (high and low-critical scenarios) suggest that crashes under ACC have an extremely low probability (an extremely long distance between collisions). Is ACC safer than manual driving? Sometimes—it depends on what manual driving style we are comparing it to. The results from EVT indicate that ACC may be associated with higher BTN (i.e., higher risk) than under a defensive, cautious human control. If a high critical scenario would occur (e.g., an event that deviates considerably from the stable, routine driving process), only an automated system would most likely prevent the collision.

2.4.1. Human control

Previous studies found that drivers would often follow a lead vehicle too closely in real-world traffic—the proportion of critical THW (i.e., THW < 1 s) can be much larger under human control than under ACC (General Motors Corporation Research and Development Center, 2005, Chapter 8; Malta et al., 2012, Chapter 4; Varotto et al., 2022). Because the typical driver's reaction time is longer than 1 s (Summala, 2000), drivers would likely crash if the vehicle in front were to brake—even more so if drivers were inattentive (Lamble et al., 1999; Markkula et al., 2016; Summala et al., 1998). Under these circumstances, the potential safety benefit of an ACC by keeping a larger headway is reasonable. However, in the data we used, human drivers maintained a much longer headway relative to ACC, so the benefits of ACC were less pronounced or absent.

The results from this analysis would have been more convincing if we used data from the on-road experiments in MEDIATOR as initially planned. Unfortunately, the Sweden on-road test with the Technology Integration (TI) prototype (Fiorentino et al., 2022)—the only experiment in real traffic that included proximity measures for computing threat metrics—was delayed. Similarly, the Sweden on-road test with the Human Factors (HF) prototype did not involve active driving by the participants or ACC (Fiorentino et al., 2022). As an alternative, we relied on external data, which could support our statistical analysis but came with certain limitations. The data from OpenACC are from vehicles driven by professional drivers on a test track (Makridis et al., 2021). The purpose of the experiments in OpenACC was not to expose vehicles to critical situations. Therefore, it is reasonable to assume that drivers kept a large safety margin to avoid any potential problem and they focused on the driving task—they were careful (Sagberg et al., 2015).

Driving is largely a self-paced task so drivers themselves actively adapt their driving to maintain a comfortable safety boundary (Engström & Aust, 2011; Summala, 2007). While in our routine driving we may follow a vehicle too closely—intentionally because we are in a hurry or unintentionally because we don't recognize that we are, in fact, too close (Taieb-Maimon & Shinar, 2001)—professional drivers in a controlled experiment may have the extra motives to prevent any issues that may delay the data collection. Therefore, our estimates are much more conservative than the one by Åsljung et al. (2017) despite using a similar method. Åsljung et al. (2017) used a much larger FOT dataset (250000 km vs. 895 km) from professional drivers in *real* traffic and their best estimate was 3×10^6 km between collisions under manual control. Their estimate is closer to the actual rear-end crash frequency in manual driving in motorways in Europe, which is around 1.3×10^6 km (Dobberstein et al., 2022, para. 6.2). The results by Åsljung et al. (2017) are more precise than ours, but their paper also highlights how sensitive some modelling decisions are, particularly with extrapolations over long time horizons. Depending on the method to fit their models, they obtained an estimate of 10^6 – 10^{10} km between crashes. In the end, the model that yielded an estimate closer to the one from crash statistics was chosen, but without that reference we would not know which model would be best.

Because the data we used turned out to represent a defensive driving style without any external perturbations of the traffic flow, the results do not agree with what we would observe in regular traffic (Dobberstein et al., 2022, para. 6.2). The difference is many orders of magnitude (1.3×10^6 km vs. 9.12×10^{92} km). However, the model was a good fit to the data (Figure 2-5, Figure 2-6, and Figure 2-7) despite the small dataset, and the Bayesian model provided a more complete inference compared to maximum likelihood estimates (Coles, 2001, Chapter 9). Validity of the results depends on the quality of the input, thus, as with most techniques, agreement with the observed data is a necessary but not sufficient condition to justify long term extrapolation (Coles, 2001, Chapter 3).

Crashes is manual driving happen for many reasons, including human factors such as inattention and distraction (National Center for Statistics and Analysis, 2022; Singh, 2015). While Mediator has shown the potential to reduce distraction (Fiorentino, A. et al., 2023, Chapter 3), it can also increase it for some drivers due to the complex HMI (Fiorentino, A. et al., 2023, Chapter 4). While the specific effects of Mediator on visual behaviour are marginal, driver monitoring systems are promising (and recommended) to reduce crashes (NCAP, 2017).

If the manual driving data in OpenACC already included some of those crash-contributing factors (e.g., inattention and fatigue), then it is plausible that EVT may yield a reasonable estimate by aggregating those factors in place of directly measuring them. In the future, one way to supplement the data is to improve the driver model. For example, everything else constant, driver's response time is the most important parameter in our braking model—minor differences can have dramatic consequences in close car-following. Thus, we could include reaction time distributions for different driver states (e.g., attentive vs. inattentive). Instead, for convenience and to reduce computational cost, we assumed that all drivers would recognize a hazard and start braking with a constant delay, see also UNECE (2022, p. 30). But analyses of crashes in naturalistic driving highlight that drivers' response depends on the urgency of the situation and their visual behaviour rather than being fixed to a specific reaction time (Engström et al., 2022; Markkula et al., 2016; Summala, 2000). Moreover, many crashes happen because of a mismatch between drivers' attention and a rapidly evolving traffic event (Summala, 2000; Victor et al., 2015). Thus, in future work, we could also include visual behaviour distributions to cover multiple driver states (see Bärgman et al., 2015), but the computational demand would increase drastically.

2.4.2. Adaptive Cruise Control (ACC)

There is little work on using EVT for safety estimation of ADASs such as ACC. Most of the literature has focused on autonomous emergency interventions (e.g., AEB). Contrary to ACC, AEB is usually active by default, and it is available in most new cars. Our results about ACC alone are promising. Both EVT and the simulated high critical scenario suggest that the crash probability of ACC is practically zero. This is what we would expect if ACC was used and worked as intended (safety by design). Based on this, Mediator could increase the overall driving safety by encouraging the use of ACC when it is most appropriate.

ACC is designed to maintain a specific, fixed time-gap, so it may make more frequent and higher braking adjustments than humans. The typical operational design domain (ODD) of ACC is highway in fair weather and infrastructure conditions. This is the traffic situation driver may be also most comfortable to delegate the vehicle control (Fiorentino, A. et al., 2023, para. 3.3.1.3). It is fair to assume that ACC is quick at adjusting speed. Some studied have documented that ACC can, instead, have longer response time than humans (Makridis et al., 2020, 2021; Raju et al., 2022). But a 2 s response time is suspiciously too long given that the minimum time gap setting of commercial ACCs is around 1.2 s. Unfortunately, we lack the core understanding on how commercial ACCs are implemented. For example, ACC may have instantaneous detection of the lead vehicle closing in, but the system may wait to brake to increase comfort. Or ACC may be tuned to intervene quickly in critical situations but to relax its operation under normal circumstances.

A platoon is an excellent driving situation to apply EVT as it provides data on prolonged exposure to close car-following and the potential for lead-vehicle conflicts. While there are fewer interferences in a test track than in real traffic (e.g., due to sensor noise or cut ins), we can assume that ACC operates in the same way both in real traffic and in closed test-tracks. Moreover, many of the interferences may become less frequent during normal use as technology improves, or they could be mitigated by supervisory systems that assess automation fitness like Mediator (Mano, D. et al., 2021).

The challenge, however, is that it remains hard to assess the safety benefit of ACC in isolation to the human factors associated with it. As with other ADASs, there may be unintended negative effects. For example, ACC can increase inattention and make drivers vulnerable to crash in situations where ACC does not operate correctly (Rudin-Brown & Parker, 2004; Smiley, 2000; Victor et al., 2018). If Mediator can promote the use of automation where is safe, and mitigate unintended driver behaviours, then driving safety will increase (Fiorentino, A. et al., 2023, Chapter 3).

2.4.3. Brake Threat Number (BTN)

There are multiple threat metrics that can be used as crash surrogate (Li et al., 2021; Westhofen et al., 2022), but the most common one—especially in the EVT literature—is the time to collision (TTC). Previous research has shown that BTN is better than TTC for studying rear-end crashes in manual driving (Åsljung et al., 2017). In addition, we argue that TTC would not make the comparison between automated and manual driving fair. In general, proximity measures such as THW and TTC do not account for differences in braking behaviour and performance. For example, based on TTC alone, ACC would be less safe than manual driving just because it keeps a shorter headway (Figure 2-3). But ACC is more consistent and rapid at adjusting the distance to the lead vehicle than humans. The advantage of BTN is that it incorporates a braking profile that allows the capture of some of the unique features of human control and ACC (e.g., brake reaction time; Table 2-1). Ideally, the brake profile used for calculating BTN could include additional system interventions (e.g., trigger warnings or autonomous interventions based on the developing lead vehicle conflict), and this would not be possible with TTC alone.

Analyses based upon BTN may need to be complemented with other metrics. For example, BTN cannot be used to make statements on the potential injury outcomes of a crash. For this, it would be better to use Δv (Bärgman et al., 2015; Kusano & Victor, 2022). Unfortunately, Δv exists only when a collision occurred, so it does not allow to extrapolate near crashes to crashes as BTN. Future work could include Δv in EVT models to estimate extreme severity crashes from observed ones.

2.5. Conclusions

In this chapter, we estimated the crash risk of automated vehicle control as compared to human control through an analysis based on EVT and data from a platoon experiment on a test-track. Overall, EVT can work with small datasets collected in a short amount of time, which is an advantage over the classic approach of using crash databases. The threat metric BTN enabled a fair comparison of human control and automation by including their specific braking behaviour and performance. The findings indicate that the risk for a read-end crash under ACC and under normal circumstances is much lower than the crash risk under manual control at the European level. However, relative to the human control baseline, EVT estimated a potentially higher risk for ACC. But the data for manual driving represented an overly defensive driving style that may not translate well to naturalistic driving. In fact, drivers usually follow a lead vehicle closer than ACC, but the data captured the opposite behaviour. Seldom, there are exceptional situations that are major perturbations of the car-following process, for example a sudden emergency braking by the vehicle in front. In this case, the fast response time of ACC can prevent the collision despite the more aggressive driving style as compared to a careful professional driver. It turns out that automation is not always better than a human driver, and in general, the safety assessment of any driving mode depends on a complex interplay between the driver, the vehicle, and the driving context. There is a need for a system like Mediator that has the ability to optimize the overall driving safety by balancing the unique abilities of humans and automation.

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3. Observed safety performance indicators

In this section, we analysed several safety performance indicators to assess, in a qualitative manner, the safety benefit of the Mediator system based on data collected from the Technology Integration (TI) prototype vehicle on-road study in Sweden. The test vehicle equipped with a L2 automation system (adaptive cruise control + lane keeping assistance). In particular, we have analysed several key safety performance indicators known from literature to greatly influence or have a significant correlation with traffic safety such as, driver distraction (Kidd & Chaudhary, 2019; Wundersitz, 2019), time to collision (), and driver reaction time (). These indicators were analysed considering the automation status (i.e., Pilot-Assist continuous mediation) and the Mediator system availability. Our starting point and hypothesis are that if drivers follow the advices of Mediator in handing in the driving control to Pilot-Assist when automation is available, then this is expected to increase safety. Here we assume that the Mediator advices are 100% correct. Thus, we adopt a two-step approach to demonstrate the potential safety benefit of the Mediator system: first we investigate whether the Mediator system increases the use of Pilot-Assist when it is available; next we investigate the impact of Pilot-Assist on the selected key safety performance indicators compared to human drivers. Section 3.1 describes briefly the on-road study context conducted by Veoneer (VEO). Section 3.2 describes the general approach, including the key safety performance indicators, and the main research questions. Section 3.3 elaborates the answers to these questions with the support of descriptive and statistical analyses. Section 3.4 summarizes the main findings and conclusions.

3.1. On-Road Study Context

In this study, 7 professional drivers participated and drove on a pre-defined route twice in row (overall ~2 h driving time). Each driver overall performed 10 drives distributed over five different days. The drives were divided into four blocks reflecting the following different configurations of Mediator: (1) complete Mediator system (drives 1-4), (2) basic system without proactive automation and time budget information (drive 5), (3) short time budget and frequent TOC suggestions (drive 6), and (4) complete Mediator system with distraction detection (drives 7-10). The route included road segments affecting automation performance and where the driver is assumed to deactivate assisted driving, or where automation would reach its limitations and deactivate itself. A display at the centre stack displayed driving relevant data (e.g., driving mode, time to automation unfitness), instructions for the driver (e.g., keep hands on steering wheel), and information about the context (e.g., construction zone). Additional LED strips on the dashboard and the steering wheel as well as ambient lighting indicated the current driving mode, the intended or necessary changes in the driving mode as well as remaining time (e.g., by different colours, brightness, and pulsation frequencies). Further, a sound system for sound alerts was implemented.

For more details, see deliverable D3.4, chapter 4 (Fiorentino et al., 2023).

3.2. Methods

The analysis includes several key safety performance indicators derived from the TI vehicle dataset: namely the driver distraction, time to collision (TTC), reaction time, and driving volatility. Driver distraction is known to be a major contributing factor to crashes (Regan et al., 2011). The driver distraction detection algorithm (*AttenD) developed by* Kircher & Ahlström, 2013, was applied in this study. The *AttenD* value can range between 0-2s. It is assumed that the driver has a buffer of 2 s when looking away from the road since glances exceeding two seconds are considered dangerous (Klauer et al., 2006). When looking away, the buffer is depleted and when looking back to the road the buffer fills up. Therefore, as the value is lower the driver is more likely to be distracted. If the buffer runs empty the driver is classified as distracted. In other words, *AttenD* is equal to 2 seconds minus the amount of time that has elapsed in an off-road glance. The outcomes of the *AttenD* algorithm have been demonstrated to correlate significantly with crash events from a large-scale naturalistic driving study (Seaman, 2017). – The Time-to-Collision (TTC) is defined as the time required for two vehicles to collide if they continue at their present speed and along the same path (Hayward, 1971). The TTC has extensively been used in literature and by the automotive industry as a Surrogate Measure of Safety (SSM) and as a trigger for collision avoidance systems (Hayward, 1972; Papazikou et al., 2019). A threshold of 1.5s has been commonly used to distinguish unsafe from safe human driver's interactions (Hayward, 1972; Farah & Azevedo, 2017). The driver reaction time - DRT, is known to have a significant influence on drivers' ability to timely react to hazardous situations (Dozza, 2013), and changes in the driving environment. It is expected that when using Mediator, drivers would have higher awareness to their surroundings and have a faster reaction time compared to when not using Mediator. Furthermore, automation systems, such as the Pilot-Assist in this study, are expected by design to have faster response time compared to humans. Therefore, we compared human versus the automation response times with and without Mediator. Lastly, based on the speed data, the driving volatility has been calculated. Driving volatility (DV) reports on the microscopic driving variations that affect the vehicle's longitudinal control (Das et al. 2022). DV measures can be applied to speed, acceleration, or jerk variations. Increases in DV indicate an increase in collision probability (Arvin et al., 2020). Mahdinia et al. (2020) introduced speed volatility as a SSM to assess the longitudinal traffic safety of vehicles involved in car-following situations.

Considering the above-mentioned safety performance indicators, the following four research questions were defined and investigated to estimate the Mediator system safety benefit:

1. Is there a difference in visual distraction when Mediator is available versus unavailable?
2. Is there a difference in TTC when Mediator is available versus unavailable, and with Polit-Assist (PA is used as the acronym in the plots (i.e., continuous mediation) versus without Pilot-Assist (NO PA)?
3. Is there a difference in relative speed volatility when Mediator is available versus unavailable and with versus without Pilot-Assist (i.e., PA versus NO PA)?
4. Is there a difference in DRT when Pilot-Assist is inactive in different drive scenarios (clusters)?

3.3. Results and Discussion

3.3.1. Question: Is there a difference in visual distraction when Mediator is available versus unavailable?

Driver distraction is a major contributing factor to crashes (Regan et al., 2011). To test if there is a difference in the mean visual distraction value when Mediator was available versus unavailable, the *AttenD* was compared between these two conditions. Figure 3-1 presents the results.

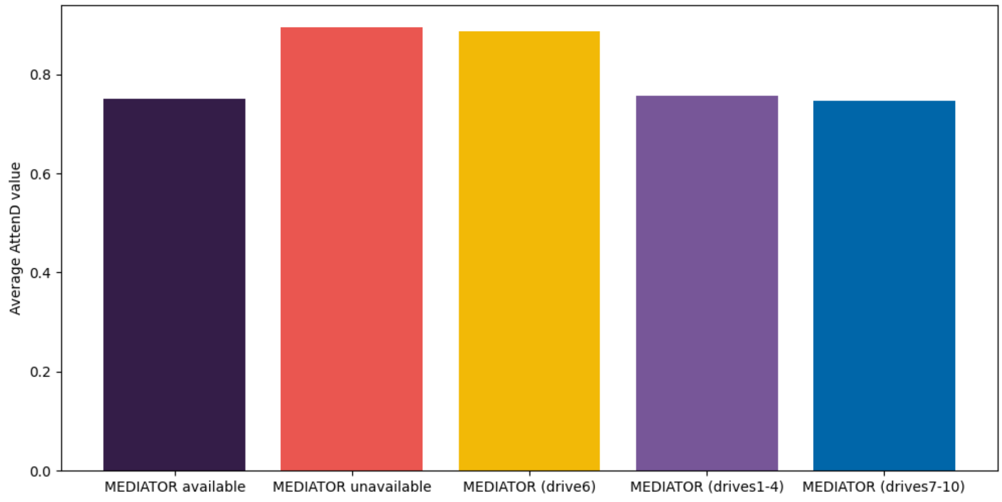

Figure 3-1: Average value of AttenD when Mediator was available versus unavailable. (Mediator available: drives 1,2,3,4, 7,8,9,10; Mediator unavailable: drive 5; Drive 6 – with short Mediator information; Drives 1-4 – full Mediator system; Drives 7-10 – full Mediator system with distraction notification).

There seems to be a difference between the two conditions. To test if this difference is significant, a repeated measures ANOVA test was conducted, and the results are presented in Table 3-1.

Table 3-1: A repeated measures ANOVA for the average AttenD value when Mediator was available versus unavailable.

Source	ddof1	ddof2	F	p-unc	ng2	eps
mediator_available	1	6	7.040212	0.037859	0.311164	1.0

The results indicate that the difference in the average AttenD values when Mediator was available versus unavailable are statistically significant, with higher AttenD value when Mediator was unavailable, indicating that the drivers were more often not looking to the forward view when driving with the Mediator system available. This result, although might appear unintuitive, can be explained by the fact that when drivers inspect the Mediator system (see experimental protocol in Deliverable 3.4, Fiorentino et al., 2023), their eyes are away from the forward view. This is also in accordance with the previous findings in Deliverable D3.4, chapter 4.4, where it was found that drivers in the full drive had a higher number of gazes at the Mediator screen compared to the no Mediator drive. Although the difference is statistically significant, it is not likely to impose higher risks compared to driving without Mediator, as the values are still close to each other, and the difference is marginal. In the case of this analysis, the difference in the mean values of AttenD is around 0.1 s, which is relatively small. In the literature, thresholds of 1.5 s and 2.0 s were used to identify looking away from the road that could lead to risky situations (Klauer et al., 2006). However, it is difficult to set one specific threshold to distinguish risky from not risky look away duration, as this depends on the specific driving context (Tivesten and Dozza, 2014). Interestingly, in previous analysis (Deliverable D3.4, chapter 4.4) it was found that drivers looked less at the Mediator screen with time, indicating that this marginal difference might vanish with time as drivers are more experienced with the Mediator system.

3.3.2. Question: Is there a difference in TTC when Mediator is available versus unavailable, and with and without Pilot-Assist?

When TTC was analysed with and without Pilot-Assist as shown in Figure 3-2, it was found that during Pilot-Assist driving (i.e., PA), TTC is larger, which indicates potential positive impact on safety when driving with Pilot-Assist control and Mediator (median of 1.3542s with Pilot-Assist compared to a median of 1.1601s without Pilot-Assist in the driving cluster with Mediator). In general, a significantly larger TTC is observed with Pilot-Assist system, compared with the Manual driving mode. Considering that the reaction time of human drivers is on average larger than what would be expected under driving with Pilot-Assist, a positive impact on traffic safety would be expected. In addition, when Mediator is activated with Pilot-Assist, the median of TTC is (significantly) higher than the one without Mediator but with Pilot-Assist (median of 1.3542s with Mediator + Pilot-Assist compared to a median of 1.2179s without Mediator + Pilot-Assist). The difference of 0.13s would translate to a distance of 4 m (i.e., about a car length), considering a driving speed of 110 km/h. This difference needs to be considered with caution as the Pilot-Assist in theory should keep the same time headway, but since there is some stochasticity, this could have resulted in this observed difference.

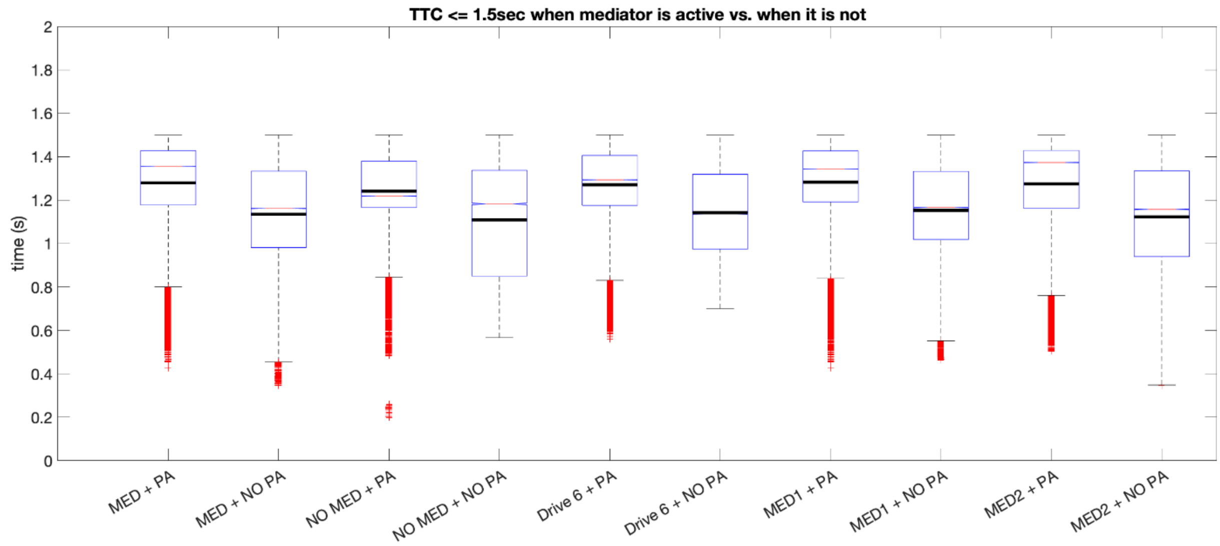

Figure 3-2: Time to collision (<= 1.5s) when Mediator was available versus unavailable, and when Pilot-Assist (PA) was available versus unavailable. MED: includes all drive scenarios (1-4 – full Mediator *system, 6 – with short* Mediator *information, 7-10 – full* Mediator *system with distraction notification); NO MED: Drive 5 – basic system without proactive automation and time budget info., MED1: includes drive scenarios of 1-4; MED2: includes drive scenarios of 7-10.*

Nonetheless, it is expected that Mediator system would encourage drivers to drive with Pilot-Assist system when it is available and within its operation conditions, increasing automation usage (which was found to be safer, see Chapter 2). Figure 3-3 shows the percentage of the highway section (in distance - km) in which drivers used Pilot-Assist normalized to the total length in which Pilot-Assist was available - with and without Mediator. The drives were divided to different clusters, MED-Drive1-4 are the first four drives with the Mediator system, No MED-Drive 5 which is the only drive without the Mediator system (very basic system without proactive automation and time budget info), MED-Drive6 is the drive with short time budgets and frequent take-over-control suggestions, and MED-Drive7-10 are the drives with the Mediator system and distraction notification. As can be seen from the boxplot, the median value of the normalized highway usage share with Mediator system (all drives) is slightly higher than the one without. Besides, as expected in drive 6 (with short time budgets and frequent take-over-control suggestions), the highway usage percentage is the highest amongst these drive clusters. Although the difference is not significant (as shown in Table 3-2), the higher highway usage percentages in the clusters suggest that Mediator can encourage increased automation usage.

Figure 3-3: Percentage of the highway section (in distance - km) in which drivers used Pilot-Assist (PA) normalized to the total length in which Pilot-Assist was available - with and without Mediator. MED: includes all drive scenarios (1-4 – full Mediator system, 6 – with short Mediator information, 7-10 – full Mediator system with distraction notification); NO MED: Drive 5 – basic system without proactive automation and time budget info.

Table 3-2: Repeated measures ANOVA of the normalized highway usage percentage Where drivers used PA amongst the different cluster of drives (all drives, 5, 6, 1-4, 7-10).

ANOVA Table					
Source	SS	df	MS	F	Prob>F
Groups	7765	4	29.7774	0.64	0.6337
Error	5846.48	126	46.4006		
Total	5965.58	130			

3.3.3. Question: Is there a difference in relative speed volatility with and without Pilot-Assist?

In this study, we have used the mean absolute deviation (*MAD*) of speed (*V*) to quantify relative speed volatility that shows variations in speed data, by measuring the distance between each observation and to their mean and then aggregated across all periods (of the same automation status) in a driving scenario/cluster, as formulated in (Equation 4-1) and (Equation 4-2)) (Das et al. 2022).

$$MAD_i = \frac{1}{T}\sum_{t=0}^{T}[V_{it} - \bar{V}_i]$$

(Equation 4-1)

$$MAD = \frac{1}{N}\sum_{i=0}^{N} MAD_i$$

(Equation 4-2)

Where, *T* denotes the period of the same automation status (with/without Pilot-Assist) with the index of *t*; *N* denotes the individual driving scenario with the index of *i*.

In general, for all the drive scenarios as shown in Figure 3-4, *MAD* is lower when driving with Pilot-Assist compared to the case when driving without Pilot-Assist. This indicates speed deviation or relative speed volatility is smaller when driving with Pilot-Assist as shown in Table 3-3, which indicates potential safety improvement (Arvin et al., 2020).

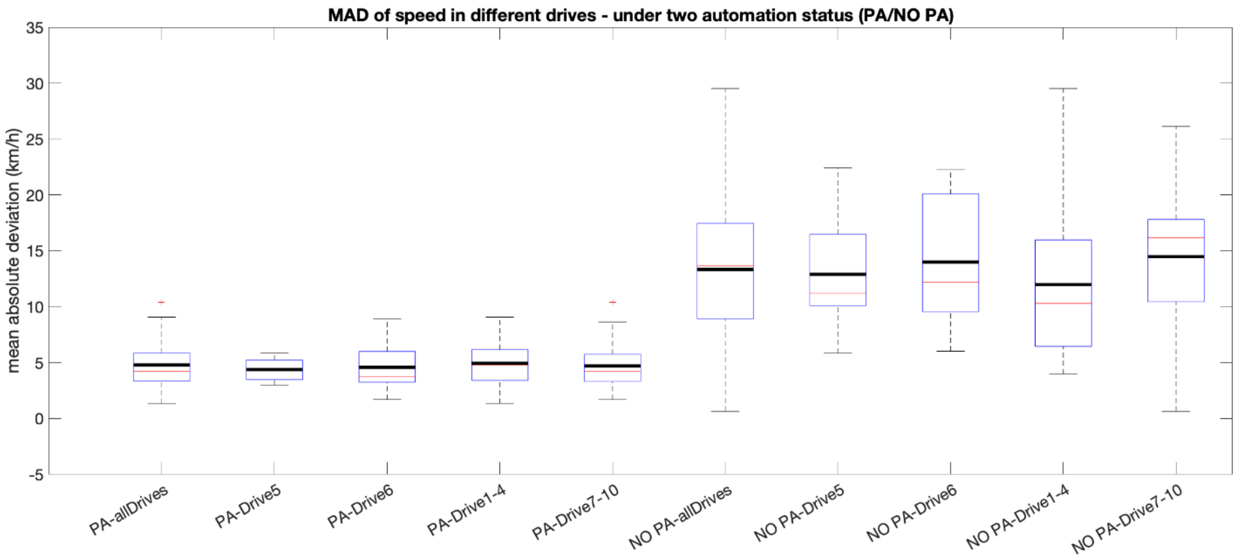

Figure 3-4: mean absolute deviation (MAD) of speed (km/h) for the different clusters- with and without Mediator – with and without Pilot-Assist. Note: Drive 1-4 – full Mediator *system; Drive 6 – with short* Mediator *information; Drive 7-10 – full* Mediator *system with distraction notification; Drive 5 – basic system.*

Table 3-3: Repeated measures ANOVA of the MAD of speed in the two driving clusters (when Pilot-Assist is ON/OFF).

ANOVA Table					
Source	SS	df	MS	F	Prob>F
Groups	4773.2	1	4773.2	234.07	4.05676e-38
Error	5301.9	260	20.39		
Total	10075.1	261			

3.3.4. Question: Is there a difference in Driver Reaction Time (DRT) when Pilot-Assist is inactive in different drive scenarios (clusters)?

The default value of DRT when Pilot-Assist is activated is set to 0.8s. When Pilot-Assist is not activated, the DRT was provided by the Mediator system, as shown in Figure 3-5.

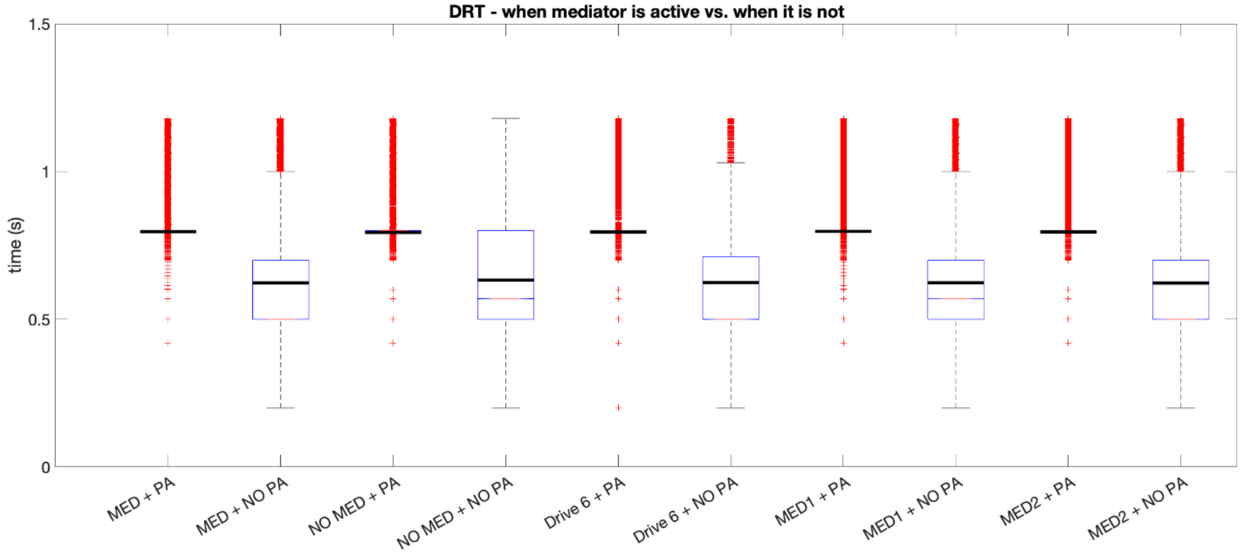

Figure 3-5: driver reaction time (DRT in second) for the different clusters- with and without Mediator – when Pilot-Assist (PA) was ON and when it was OFF. MED: includes all drive scenarios (1-4 – full Mediator *system, 6 – with short* Mediator *information, 7-10 – full* Mediator *system with distraction notification); NO MED: Drive 5 – basic system without proactive automation and time budget info., MED1: includes drive scenarios of 1-4; MED2: includes drive scenarios of 7-10.*

There is a significant difference in DRT between the cases for different driving orders (from 1 to 10 runs) but not for the cases when Mediator is active or not (as evidenced by a multilevel mixed effects model analysis in Table 3-4). It is logical to observe the DRT decreases as the driving repetition increases. Nonetheless, the result shows that drivers in the drives with the Mediator system (without Pilot-Assist) react a bit faster (smaller) than the case without the Mediator system (without Pilot-Assist) (Median DRT of 0.54s vs. 0.57s). This implies that Mediator might have a small positive impact on improving driver reaction time.

Table 3-4: Multilevel mixed-effects model analysis of the DRT (s) regarding the conditions of different drives, different drivers, and different Mediator *availability statues when Pilot-Assist is OFF.*

Multilevel mixed-effects model – fixed effects coefficients							
Name	Estimate	SE	tStat	DF	pValue	Lower	Upper
'Intercept'	0.62675	0.013217	47.421	2.7575e+06	0	0.60084	0.65265
'Driving order'	-0.0014453	0.00043311	-3.3372	2.7575e+06	0.00084642	-0.0022942	-0.00059647
'MED status'	-0.0004084	0.0041428	-0.09858	2.7575e+06	0.92147	-0.0085282	0.0077114

3.4. Summary & Conclusions

In general, driving with the Mediator system available based on the limited data collected from the TI in-vehicle prototype field test (7 professional drivers) is shown to have marginal positive impact on safety. Drivers in the drives with Mediator reacted a bit faster than the case without Mediator, although the magnitude of this difference is small. The Mediator HMI design had two primary functions (Deliverable D3.3, Borowsky et al., 2023): to increase mode awareness and to prevent drivers from becoming fatigued or distracted (preventive mediation) or have degraded performance (corrective mediation). These functionalities considered in the design of the HMI might explain why drivers react a bit faster than in the case without Mediator. Furthermore, driving with Pilot-Assist is shown to improve the driving performance in terms of the surrogate safety measures tested, such as Time-To-Collison and driving speed volatility. The higher usage of the Pilot-Assist on the highway when driving with Mediator (when Pilot-Assist is available), suggests that Mediator can encourage automation usage (i.e., using Pilot-Assist when it is available). This would potentially have positive impact on safety in terms of the time-to-collision and speed volatility; though the findings were not significant they indicated a positive effect. Finally, marginal (although significant) difference in driver *AttenD* and *Distraction* values were found compared to driving without Mediator, but it is not likely to impose higher risks as the differences in their mean values is small.

In spite of the seemingly positive results, it is important to highlight, however, that these observations are based on an exploratory study with limited data set of 7 professional drivers who participated in the field test on a specific testing environment. Therefore, the results from this analysis and the observations made should be considered carefully, and further research needs to be conducted to reach firm conclusions about the safety impacts of the Mediator system and to have external validity. Because of the small sample size of participants and as well the relatively simple driving conditions, no further extrapolation to quantify the reduction in traffic crash numbers was conducted. It is recommended to consider in future research bigger sample of participating drivers, with different demographic characteristics (e.g., age, gender) as well as driving experience. Furthermore, as a first on-road study to test a new technology, and for ethical reasons, the testing environment was relatively controlled to be conducted in non-complex traffic situations and relatively good weather conditions. Therefore, it is recommended in future research to conduct the field tests in different driving conditions (e.g., weather and visibility, traffic intensity).

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4. Estimated societal benefits

Mediator is a system that mediates between the human driver and the automated driving system to enable safe, real-time switching between both based on the respective fitness to handle the current and upcoming driving situations. Important variables are (1) driver's fitness / unfitness (e.g., impaired driver states like distraction, fatigue, discomfort), (2) automation fitness / unfitness (e.g., reaching end of ODD, reliability of sensors), and (3) environmental conditions (e.g., weather, traffic jams, highway exits). Hence, Mediator is a system built on top of existing automated driving systems designed to ensure, for instance, correct usage of automated driving systems, increased predictability, quality and smoothness of take-over actions, prevention of mode confusion as well as ensuring safe driving by avoiding manual driving with impaired driver states. Therefore, Mediator is intended to increase road safety and to reduce the societal burden of crashes. There are several factors that are particularly important when considering the societal impact. The acceptance of the system and the manner of usage, the extent to which Mediator reduces unfit manual driving and the impact of the system on the transition of control.

The expected societal benefits of Mediator will depend to a large extent on the actual use of the system. With the help of a simulator study (Athmer et al., 2022), we showed that 86 % of the test persons expect an increase in safety (e.g., through a reduced number of crashes) when Mediator is activated. We know from previous project Deliverables, that 88 % of the test subjects stated that they would use Mediator in their own car (Borowsky et al., 2023). However, it should be mentioned that the sample is naturally characterized by its interest in the topic and the likelihood of an increased acceptance rate is possible, which might not be found in reality in such a way. The results from the field studies in Italy replicate this positive feedback (Fiorentino et al., 2023). Moreover, if Mediator actually leads to a reduction in collisions or less serious collisions depends, among other things, on the distraction potential of the system. In addition, there is the possibility that drivers use Mediator to engage in other secondary activities, which in turn distract them from checking Mediator. The FCA Sweden study showed that continuous Mediation resulted in less distraction than a baseline condition and lower average maximum duration of a distraction (Fiorentino et al., 2023).

In the following, the influence of Mediator usage on the frequency of rear-end collisions and the associated social costs will be analysed. The underlying assumption is the following: Using Mediator increases the correct usage of automated driving systems (e.g., when approaching a traffic jam) which can reduce the amount of rear-end collisions, e.g., due to human drivers' inattention. In addition, it has a positive impact on traffic flow and reduces the number of rear-end collisions of the vehicle with mediation (Chapter 4). For this purpose, societal costs will be defined at the beginning. Subsequently, aggregated statistics on rear-end collisions in Europe with different severity levels (slight, serious) resulting in different levels of crash costs are presented. Socio-economic savings and the potential for rear-end crash prevention are calculated based on international statistics, specific assumptions about Mediator, and the results of WP3 studies and literature (e.g., activated automation would prevent every rear-end crash in traffic jams). Finally, the results will be discussed.

4.1. Definition of societal burden due to crashes

Information about the costs provides an insight in the consequences of road crashes for the economy and social welfare, and it is used in cost-benefit analyses in order to estimate the social return of investments in road safety and to prioritize (road safety) measures.

European Guideline COST 313 (Alfaro et al. 1994) defines five components of the costs of road crashes.

- **Medical costs:** costs resulting from the treatment of casualties, e.g., costs of hospital stay, rehabilitation, medicines and adaptations for the handicapped
- **Production loss:** loss of production and income resulting from the temporary or permanent disability of the injured, and the complete loss of production of fatalities.

- **Human costs:** immaterial costs through suffering, pain, sorrow and loss of quality of life.
- **Property damage**: damage to vehicles, freights, roads and fixed roadside objects.
- **Administrative costs**: in this category costs of police, fire brigade, law courts and administrative costs of insurers are taken into account.

The definition of the cost types can be found in the Appendix B .

4.2. Standard unit for collision costs

The basis for estimating social benefits of using Mediator is the annual number of crashes covering the scenario of potential rear-end collisions. Therefore, absolute numbers of the different severity levels (casualties, seriously injured, slightly injured, property damage) are needed. It also requires knowledge of the cost of a single collision as a function of severity. The calculation of these unit costs varies, of course, depending on the approach used by the different (European) countries. Wijnen et al. (2017) proposed a method for the calculation of these costs (human costs, medical costs, production losses, administrative costs, material damage) and established crash costs for 27+3 European countries within the SafetyCube project. The SafetyCube data and calculation method were the basis for the costs calculated in the L3 pilot project, in which the financial level of the year 2020 was adjusted. Table 4-1 shows the assumed standard unit costs per crash severity.

Table 4-1. Standard unit costs (in €) for total crash costs by casualty severity according to L3 Pilot (2020 prices).

Crash severity	Human Costs	Medical Costs	Production Loss	Administrative Costs	Property damage	Total Unit crash costs
Fatality	3,505,386	12,521	774,911	9,469	18,682	4,320,970
Serious injury	562,017	20,403	53,554	5,918	11,867	653,760
Slight injury	51,401	2,084	3,865	2,851	7,701	67,903
Property damage only				814	2,977	3,791

4.3. Research findings & crash rates

In order to make assumptions about the amount of cost savings, it is necessary to know the basic rates of scenarios of interest. One scenario, the MEDIATOR project focuses on, is rear-end collisions. There are few statistics detailing the frequency of different types of crashes. The amount of financial expense caused by a crash also varies from country to country. In the following, we will report the share of crash costs in gross domestic product (GDP) by country and provide findings on the share of individual cost components. Based on these findings, we present the calculation basis for the approach we use to determine societal costs. For this purpose, we present a variety of (inter)national statistics to determine the frequency of rear-end collisions with the aim of estimating the societal costs eventually.

The International Transport Forum's (ITF, 2021) annual report on road safety contains the costs of road crashes for the 38 OECD countries (Appendix B . Expenses is given as a percentage of the GDP. On average, the costs amounted to approx. 1.64 % of the GDP. In general, the comparability of the data is somewhat difficult, as data are not always available for all categories of crashes. Chen et al. (2019) estimated the effect of road injuries on the economic output for 166 countries. Data has been derived from the World Bank database. Out of 166, 138 countries provided a complete dataset. According to the researchers, high income countries (HIC) have the largest economic costs of road injuries.

The European accident database (CARE, 2011) project stated that approximately 16 % (18,200) of all 1.1 million collisions in 2010 were rear-end collisions. This represents 6 % of the 30,800 fatalities in 2010 in the EU. More recent and comprehensive data sets for rear-end collisions in Europe are not available. The basis for our calculations of societal costs is prevalence data from country-specific statistics from 2019 and 2020. Data from 2019 does not contain the rapid decrease in motorized individualized transport caused by the Corona pandemic starting in 2020. Data from 2019 is likely to be more valid for estimating (monetary) losses from such incidents than from the year 2020. However, increasingly installed safety technologies also reduce the number of collisions in general. In addition, rising inflation means that calculated costs probably underestimate real costs. When reviewing country-specific statistics, it is also important to consider the precise locations where the crashes occurred. In MEDIATOR, rear-end collisions on the highway were investigated (Borowsky et al., 2022). Before mentioned statistics do not always provide information of rear-end collisions on the highway. When available, a distinction was made between intra- and extra-urban areas in the datasets. However, this information does not reveal whether a rear-end collision occurred on the highway or not. The numbers can, at least, serve as an anchor for estimations. Furthermore, different crash severity levels are reported in the statistics. Incidents are often subdivided into slight and severe casualties, as well as crashes without injuries and with property damage only. As already mentioned in the previous paragraph section (Standard unit accident costs), the expenses vary as a function of the severity of the injury. Rear-end collisions can result in any of the above degrees of injury.

In addition, it must be considered that the underlying system (e.g., AEB) does not prevent crashes in 100 % of cases. Different studies suggest that in the case of rear-end collisions, e.g., by using AEB, an estimated 50% of crashes are prevented (Jeong, & Oh, 2013, Cicchino, 2016, Tan et al., 2020).

For the MEDIATOR scenario under consideration, statistics from Europe are considered exclusively. To illustrate the procedure, we use the data from Germany as an example. Data from The Netherlands, Switzerland and Austria are attached in the Appendix B .

The German Federal Statistical Office publishes annual statistics on crashes (Statista Research Department, 2022). The number of traffic crashes rose steadily in Germany until 2019. The numbers for rear-end collisions for 2019 and 2020 are shown below in Table 4-2 (Statistisches Bundesamt, 2021a, 2021b). According to the Federal Statistical Office the costs incurred as a result of crashes amounted to approximately 33,9 billion euros in 2019. In 2021, the total number of crashes increased, but the number of crashes with personal injury decreased. Evaluations of crashes with casualties and crashes with personal injury appear in the statistics. The difference lies in the fact that a collision can have several casualties. At the same time, such a collision counts only as one crash event with personal injury (no matter how many injured/crash victims there were). Therefore, in the statistics, the number of casualties is usually higher than the number of crashes with personal injury.

Table 4-2 Frequency of rear-end road crashes with personal injury, casualties, and serious crashes with property damage in Germany in 2019 and 2020.

	Crashes with personal injury		**Casualties**		**Serious crashes with property damage**	
	Intra-urban	Extra-urban	Intra-urban	Extra-urban	Intra-urban	Extra-urban
2019						
Total	29,305	22,802	38,511	37,817	1,592	2,490
Killed	26	251	27	266		
Seriously injured	1,675	3,333	1,829	4,446		
Slightly injured	27,604	19,218	37,655	33,105		
2020						
Total	23,553	17,194	30,960	27,731	1,250	1,838

	Crashes with personal injury		Casualties		Serious crashes with property damage
Killed	15	175	15	187	
Seriously injured	1,383	2,771	1,507	3,569	
Slightly injured	22,155	14,248	29,438	23,975	

4.4. Financial societal benefits

The following assumptions about the number and cost of prevented crashes are based on the assumption that mediator is a system that builds on an existing automated driving system. Mediator is designed to provide recommendations for automated driving based on driver fitness (Unfitness, e.g., driver states like distraction, fatigue, discomfort), automation fitness (e.g., reaching end of ODD, reliability of sensors), and the environment (e.g., weather, traffic jams, highway exits). Mediator is not mandatory. The driver decides if his car is equipped with this system and if the system is activated during a trip. In addition, the driver decides whether to follow or ignore the recommendations. The following results represent a best-case scenario in terms of avoided rear-end collisions. With a reduction of the acceptance rate or the willingness to buy, the number of avoided crashes is naturally decreasing.

In the following, the number of preventable rear-end collisions due to the use of Mediator as well as the monetary savings are presented. To illustrate the procedure, we use the data from Germany as an example and extrapolate to the European level. The data from the previous section (Standard unit accident costs; Rear-end collision frequency) forms the basis for the calculations. The crash costs are estimated by including all the main cost components: Human costs, medical costs, production loss, administrative costs and property damage. For a realistic result the standard unit cost is multiplied by the 88 % acceptance rate identified in the TUC simulator study (i.e., 88 % of drivers indicated to use Mediator in their future cars if the system will be available, Borowsky et al., 2023). We assume, that the Mediator system increases the use of these other systems by 88 %. The driving task is a conglomerate of driver, vehicle and environment. Errors can occur on the driver side as well as on the vehicle side (sensors) depending on the environmental conditions, e.g., fog, rainfall (Roh et al., 2020). Therefore, it is also essential to consider the system reliability. In relation to the project and calculations, this means that underlying system Mediator is referring to can also be a source of errors and, in addition to false alarms, can also produce failures. It follows that lower system reliability leads to higher costs. As already mentioned, it can be assumed that not all rear-end collisions can be avoided. Therefore, based on existing research results, a 50 % effectiveness of the underlying system is assumed in the following.

In 2019 and 2020, respectively, there were 143,189 rear-end collisions in Germany. Of these, 40,307 in 2019 and 29,569 in 2020 were extra-urban. Therefore, with an acceptance rate of 88 % and under the assumption that by using Mediator the automated driving system would have been activated before approaching a traffic jam and that the automated driving system would have prevented 50 % of rear-end collisions, 17,738 rear-end collisions in 2019 and 13,012 rear-end collisions in 2020 could have been prevented with the help of Mediator. The frequencies of preventable extra-urban rear-end collisions according to severity are shown in Table 4-3.

Table 4-3 Number of prevented extra-urban crashes according to severity level in 2019 and 2020 in Germany (acceptance rate = 88 %, effectiveness rate= 50 %).

Severity level	2019	2020
Casualties	118	83
Serious injuries	1,957	1,571
Slight injuries	14,567	10,549
Property damage	1,096	809
Total crashes prevented	17,738	13,012

The assumed total savings from the use of Mediator for extra-urban rear-end collisions would have amounted to 2,443,812,504 € on average in Germany in 2019 or 2020. Detailed information on the individual cost components can be found in Table 4-4 and Table 4-5. According to the Federal Highway Research Institute (BASt) the total crash costs for 2019 were 36,85 billion and 31,47 billion in 2020. The total costs that could have been prevented by using Mediator in 2019 amount to around 2,78 billion €. In 2020, it was around 2,10 billion €. Relative to the gross domestic product, this represents around 0.008 % of GDP in 2019 and 0.007 % of GDP in 2020. This is roughly 1 % of the cost of traffic crashes in 2020 in Germany according to data provided by Chen et al. (2019).

Table 4-4 Prevented costs (in €) according to severity level for extra-urban collisions in 2019 in Germany (acceptance rate = 88 %, effectiveness rate= 50 %).

Severity level	Human costs	Medical costs	Product-ion loss	Administrative costs	Property damage	Total
Casualties	413,635,548	1,477,478	91,439,498	1,117,342	2,204,476	509,874,342
Serious injuries	1,099,867,269	39,928,671	104,805,178	11,581,526	23,223,719	1,279,406,363
Slight injuries	748,758,367	30,357,628	56,301,455	41,530,517	112,180,467	989,128,434
Property damage				892,144	3,262,792	4,154,936

Table 4-5 Prevented costs (in €) according to severity level for extra-urban collisions in 2020 in Germany (acceptance rate = 88 % effectiveness rate= 50 %).

Severity level	Human costs	Medical costs	Production loss	Administrative costs	Property damage	Total
Casualties	290,947,038	1,039,243	64,317,613	785,927	1,550,606	358,640,427
Serious injuries	882,928,707	32,053,113	84,133,334	9,297,178	18,643,057	1,027,055,389
Slight injuries	542,229,149	21,984,116	40,771,885	30,075,199	81,237,849	716,298,198
Property damage				658,526	2,408,393	3,066,919

The statistics provided in the previous tables are estimates to make assumptions about the hypothetical savings caused by rear-end collisions at the European level. Data for The Netherlands, Switzerland and Austria can be found in the Appendix B .

In summary, it can be assumed that with 50 % system effectiveness and an 88 % acceptance rate of the Mediator system, about 44 % of all rear-end collisions could be prevented. Overall, this corresponds to between 0.005 % and 0.1 % of the gross domestic product of the relevant country.

Table 4-6 Summary of the % GDP characteristics of Chen et al (2020) and the results of our calculations on financial societal benefits of Mediator in 2019 and 2020.

Country	% of road injuries costs on GDP[1]	reference year[1]	% of savings on GDP in 2019	% of savings on GDP in 2020
Austria	3.3	2016	0.09	0.07
Germany	0.9	2020	< 0.01	< 0.01
Netherlands	2.0	2018	< 0.01	< 0.01
Switzerland	2.4	2017	0.02	< 0.02

Note: [1] = Chen et al. (2019)

In more detail, Table 4-7 and Table 4-8 display the cost components depending on the country (which we found information for) for the years 2019 and 2020. As can also be seen in Figure 4-1, a large proportion (approx. 73 %) of the costs caused by rear-end collisions is immaterial costs through suffering, pain, sorrow and loss of quality of life. This is followed by property damage costs (approx. 13 %), production loss (approx. 8 %) and administrative costs (approx. 4 %) and finally medical costs (2 %).

Table 4-7. Expenditure on cost components (in €) for rear-end collisions by country and in total in 2019.

Country	Human costs	Medical costs	Production loss	Administrative costs	Property damage
Austria	310.418.324	10.511.968	31.522.596	14.258.252	38.403.460
Germany*	2.262.261.184	71.763.777	252.546.131	55.121.529	140.871.454
Netherland*	26.419.303	423.137	4.543.200	1.812.036	6.075.757
Switzerland	99.143.628	3.495.018	9.632.676	5.163.616	15.278.392
Total	2.698.242.439	86.193.900	298.244.603	76.355.433	200.629.063

** extra-urban only*

Table 4-8. Expenditure on cost components (in €) for rear-end collisions by country and in total in 2020.

Country	Human costs	Medical costs	Production loss	Administrative costs	Property damage
Austria	227.005.430	7.648.484	23.205.202	10.371.526	27.932.382
Germany*	1.716.104.894	55.076.472	189.222.832	40.816.830	103.839.905
Netherland*	8.337.080	208.417	1.138.221	895.289	3.002.119
Switzerland	78.788.341	2.705.485	7.932.686	4.108.164	12.197.380
Total	2.030.235.745	65.638.858	221.498.941	56.191.809	146.971.786

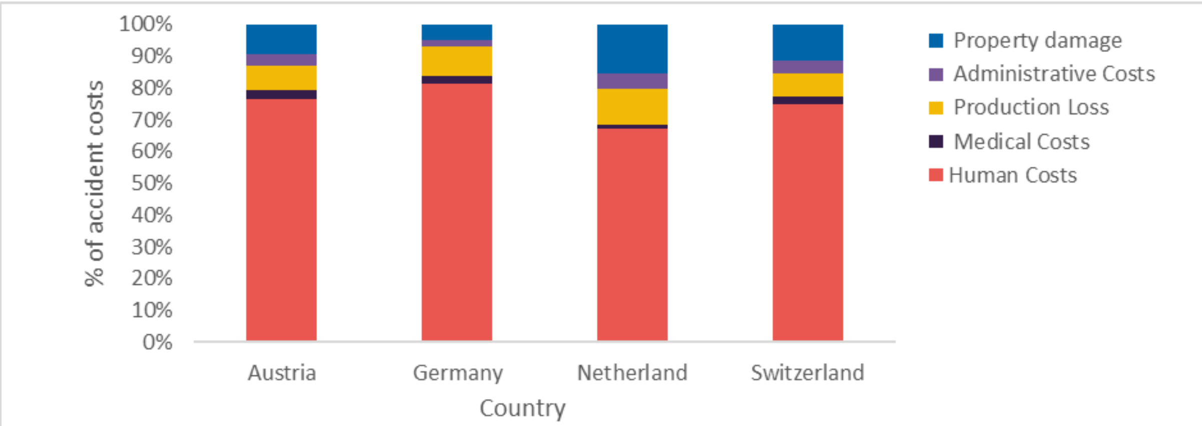

Figure 4-1. Share of costs as a percentage of total costs by cost component and country (2019 and 2020).

In 2019, the overall GDP of the European Union (EU27) was 14,02 trillion Euros. The range of the GDP saving percentage for rear-end collisions from countries whose statistics we found in our review is between 0.005 % and 0.021 %. With these percentages as a basis, the use of Mediator could save hypothetically between 701 million and 2,95 billion euros on a European level in 2019.

In 2020, the overall GDP of the European Union (EU27) was 13,40 trillion Euros. The range of the GDP saving percentage for rear-end collisions from countries whose statistics we found in our review is between 0.002% and 0.074 %. With these percentages as a basis, the use of Mediator could save between 280 million and 9,16 billion euros on a European level in 2020.

4.5. Conclusion

The amount of casualties, slight and serious injuries and property damage avoided by using the mediator system varies depending on the country-specific base rate of relevant rear-end crashes. From recent studies within the project, it became clear that around 88 % of the drivers who tested Mediator in a driving simulator study would also use it in their private cars. Therefore, we have assumed a market penetration of 88 %. Economists should determine how the penetration rate can be in reality. With a reduction of the acceptance rate or the willingness to buy, the number of avoided rear-end collisions is naturally decreasing, which in turn lowers the financial benefits of Mediator.

In the financial societal analysis, emphasis was placed on the prevented traffic crash costs in terms of percentage of GDP. It should be noted that the choice of method for calculating the standard unit cost of a crash has a major impact on the level of crash costs. In this respect, we have oriented on projects with a similar focus and included standard values proposed there as a basis for the benefit analysis.

The reliability of the system must be considered as well. In terms of the project and the calculations, this means that the system Mediator is referring to can also be a source of errors and produce failures as well as false alarms. However, Mediator is merely an agent between the car and the driver and does not intervene in the driving task. It follows that lower system reliability can only avoid a certain number of crashes.

Based on the basic considerations of Mediator's functionality, the benefits of its use would be beyond rear-end collisions investigated at this point. As mentioned earlier, Mediator was also developed to provide recommendations for automated driving based on driver fitness (unfitness, e.g., driver conditions such as distraction, fatigue, discomfort), automation fitness (e.g., reaching the end of ODD, sensor reliability), and environment (e.g., weather, congestion, highway exits). The crash data referred to in this report are for rear-end collisions only. The effect on crash costs caused by e.g., distraction, fatigue and discomfort, or environmental factors has not been calculated at this time. It can therefore be assumed that Mediator has far more potential in reducing crash rates and in reducing costs in the future.

4.6. References

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5. Estimated performance in traffic flow

This study focuses on the effects of the Mediator system on the surrounding traffic flow. Due to its main features and operations, the Mediator system is expected to affect locally the behaviour of the surrounding traffic. Indeed, this system leads to a change in the driving style of a driver, which involves a change in the stimuli given to the surrounding vehicles. Therefore, the effects of the Mediator system on traffic congestion can be evaluated based on the behaviours induced by the vehicle equipped by this system (TI in-vehicle prototype) on surrounding vehicles.

To achieve this goal, in this study the effects on a platoon of vehicles following the “virtual” TI in-vehicle prototype are evaluated by employing data from field-experiment. More in detail, real-world driving data collected from TI in-vehicle prototype are exploited to recreate the motion behaviour of the Mediator-equipped vehicle in the virtual simulation environment. Subsequently, the longitudinal motion of surrounding vehicles is influenced by car-following models. In so doing, the motion of and interaction among vehicles (in this case the possible disturbances induced by the different speed and acceleration of the TI in-vehicle prototype) can be captured. That is, in the macroscopic traffic flow framework (Ni, 2015), understand how drivers adjust their motion in response to traffic in their vicinity. A similar approach can be found in Chang et al. (2019) and references therein. Moreover, it is worth noting that a more stable and homogeneous behaviour of the drivers leads to a safer traffic condition. Indeed, having more correct behaviour leads to a reduction in conflicts and, therefore, a reduction in the probability of collisions. Different types of surrounding drivers are emulated to account for different possible response to the behaviour of the virtual TI in-vehicle prototype. Finally, the impact of the Mediator-system is quantitatively evaluated by means of several Key Performance Indicators (KPIs). It is worth noting that this study uses different KPIs from those already defined in deliverables deliverable D1.2 as the effect of the mediator system on traffic congestion has not been the subject of previous studies within the project.

5.1. Methods

Car-following driving condition is used as a proxy to understand how other drivers respond to stimulus coming from the virtual TI in-vehicle prototype. It is worth noting that the term “virtual” is used to clearly distinguish the real version of the vehicle form the virtual one (the one that is emulated in the simulation).

Considering the point above, the considered driving condition is here recreated through a platoon of seven vehicles, where the virtual TI in-vehicle prototype (labelled with i=0) is the leader and the other six vehicles the followers. The platoon travels along a one-lane straight road (hence no lane change manoeuvres occur) and the Mediator-equipped vehicle moves according to real-world driving speed profiles. The longitudinal motion of each follower i (i = 1, …, 6) is emulated via the Krauss car-following model (Krauß, 1998). This setup allows to evaluate the impact of the Mediator system (recreated via the real speed profile) on the motion of the followers’ vehicles.

To simulate the traffic environment, a simulation platform combining MATLAB/SIMULINK and SUMO (Lopez et al., 2018) has been established.

In what follows, the preparatory steps for the main analysis are introduced and explained. A more detailed explanation of the employed methods is reported in Appendix.

5.1.1. Data Extraction

Real-world driving data collected from the TI in-vehicle prototype refer to the whole testing route. However, this study mainly considers the drives on segments categorised as “highway” of the selected route for the on-road study. Hence, the considered real-world driving speed profiles refer to these specific segments only.

More specifically, two sub-routes can be extracted from the complete one, as shown in Figure 5-1. Namely, the sub-route 1 (blue line in Figure 5-1) consisting mostly of the motorway connecting Vårgårda to Alingsås, while sub-route 2 (red line in Figure 5-1) consists of the motorway connecting Alingsås to Vårgårda. In the performed analysis, the two considered sub-routes are investigated separately so to account for possible variations in the behaviour of drivers and/or traffic conditions.

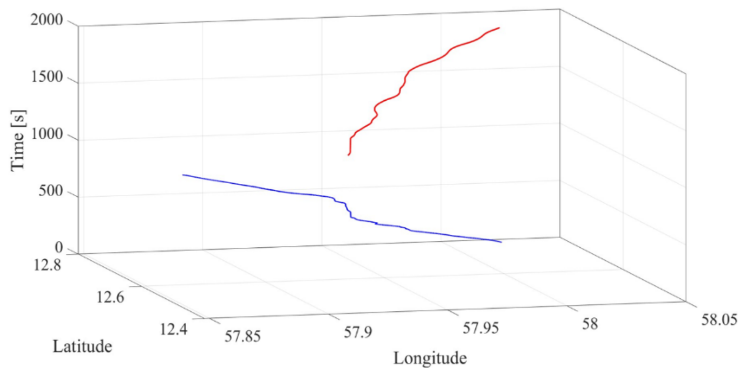

Figure 5-1 – Considered highway sub-routes.

Regarding the drives, the following ones are considered:

- Drives 1-4: *full system* (120 [s]– first (voice) and 30 [s] (sound)) - 21 complete drives available for each sub-route;
- Drives 5: very *basic system* without proactive automation and time budget info – 5 complete drives available for each sub-route;
- Drives 7-10: *full system with distraction* - 25 complete drives available for each sub-route.

It is worth noting that Drive 6 has been discarded since no complete data for the considered sub-route were available.

The effect of each configuration of the Mediator system is analysed separately to spot the effect of each of them on the surrounding vehicles.

5.1.2. Testing Scenarios and Key Performance Indicators

The longitudinal motion of *i*-th follower (*i* = 1, …, 6) is modelled according to the car-following model proposed by Krauß (1998). This is described in detail in Appendix C Since the effects of the system on the followers' vehicles is influenced by the behaviour of the followers, in the study we consider two sets of car-following parameters values to mimic the behaviour of human drivers from different European countries. In what follows, we use the following notation for the sets:

1. set-1: set of car-following parameters for Austrian drivers taken from the technical literature (Berrazouane et al., 2019);
2. set-2: set of car-following parameters for Swedish drivers shared by TU-Delft.

The parameters, their description and relative values are reported Table 5-1.

Table 5-1 – Krauss car-following parameters for the two considered sets.

Parameter	Description	Set-1	Set-2
a [m/s2]	The vehicle's acceleration ability	2.786	0.8
b [m/s2]	The vehicle's deceleration ability	7.424	8
h [s]	The desired minimum time-gap	1	0.4
dst [m]	Standstill distance	2.377	2.5
τ [s]	Reaction time	1	0.4

It is worth noting that, to properly run simulations and avoid unexpected behaviours and collisions among vehicles, SUMO requires a value of action and reaction time [s] lower or equal to h, the desired minimum time-gap. Accordingly, it is fixed at the same value of h for each considered set of parameters.

To evaluate the impact of the Mediator system on driving behaviours of the followers, four experimental scenarios are designed:

1. A-I: sub-route 1 with set-1 of car-following parameters values;
2. A-II: sub-route 2 with set-1 of car-following parameters values;
3. B-I: sub-route 1 with set-2 of car-following parameters values;
4. B-II: sub-route 2 with set-2 of car-following parameters values.

Finally, to compare the performance of the different Mediator system configurations on the surrounding traffic, the following KPIs are considered:

- Maximum decelerations [m/s^2], the lowest value of deceleration observed in each single simulation run.
- Standard deviation of speed [m/s], a proxy of the magnitude of the speed variation along the journey;
- Aggregated Speed Volatility [m/s], which measures the driving variations that occur in the speed profile (Mahdinia et al., 2020).

5.2. Results and Discussion

In this section we report and discuss about the results obtained with the simulation analysis described in Section 5.1. In what follows, to help the readers, we will use red colour for the *full system* configuration, blue colour for the basic system configuration and yellow colour for *full system with distraction* configuration.

5.2.1. Scenario A-I

The scenario A-I involves the sub-route 1 (the motorway stretch connecting Vårgårda to Alingsås, see Figure 5-1) and the set-1 of values of car-following parameters in Table 5-1.

The first analysed KPI is the max deceleration. For each simulation run, the higher value of deceleration is considered. It is worth to recall that the number of runs is not the same for the different drives.

Boxplots in Figure 5-2 show the distribution of the maximum value of deceleration for each follower in the platoon. The y-axis refers to the deceleration, while the x-axis refers to each different follower in each different drive. For the sake of readability, as already stated in Section 5.2, a specific colour has been linked with each different group of drives. Moreover, followers are placed in groups of three in the boxplot, so to better compare the performance of the same follower in different drives.

The outcome of Figure 5-2 shows that, on average (the median), the results of *full system* and *basic system* configurations are very similar to each other. However, the *full system* distributions have the lowest dispersion, indicating a more homogeneous behaviour. Results clearly highlight that the *full system with distraction* configuration performs the worst, since they have the lowest median value and the larger dispersion. Moreover, strong decelerations occur in the *full system with distraction* configuration, which could lead to unsafe braking manoeuvres due to the sudden variation of the speed.

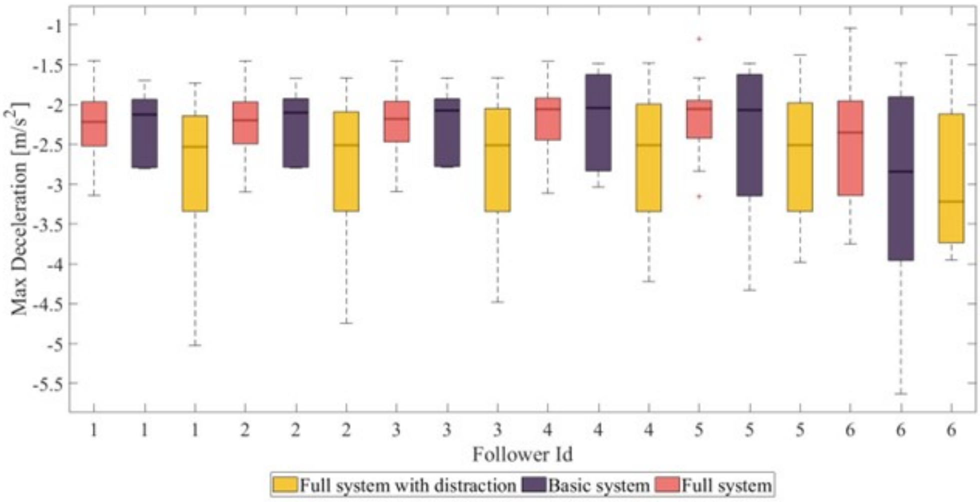

Figure 5-2 – Scenario A-I. Boxplot of the maximum deceleration of each follower i in the platoon (i = 1, …, 6). Red refers to fully system configuration, blue to basic system configuration and yellow to fully system with distraction configuration.

Sudden variation of the speed could produce considerable oscillations in the follower's motion. In this perspective, we compute the average standard deviation of the speed and the average speed volatility.

Regarding the standard deviation of the speed, the results in Figure 5-3 show that the *full system* configuration presents the lowest median values (for all followers) with respect to the *basic system* and the *full system with distraction* configurations. This outcome proves that the *full system* configuration leads to, on average, a more stable behaviour of followers than other configurations. That is, minor fluctuations of the speed occur. In this scenario, the worst case in terms of average behaviour is represented by the *full system with distraction* configuration, which have the higher median value of standard deviation of speed. Moreover, even if the distributions of these latter drives are the less dispersed (more homogeneous behaviour), they are shifted towards high values of speed standard deviation; this implies a less stable behaviour of the followers in the platoon.

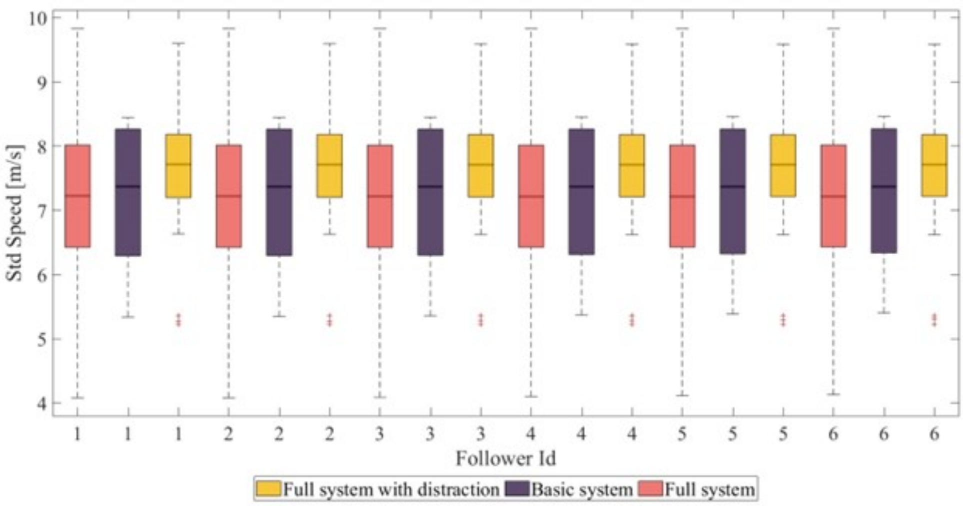

Figure 5-3 – Scenario A-I. Boxplot of the standard deviation of the speed of each follower i in the platoon (i = 1, …, 6). Red refers to fully system configuration, blue to basic system configuration and yellow to fully system with distraction configuration.

To link the variation in the speed data along the whole travelled path with the probability that a collision occurs, the Aggregated Speed Volatility is computed as defined in 0. More specifically, the Speed Volatility is computed for each follower *i* (*i* = 1, …, 6) in the platoon and then, aggregated across all of them. Related distributions, referring to each drive group, are reported in Figure 5-4. The findings highlight that the *full system* and the *basic system* configurations led to a comparable median behaviour, with this latter having a slightly lower median value with respect to the former (-1.26 % with respect to the *basic system*). Considering the whole distribution, it is possible to observe better performance with the *full system* configuration than the *basic system* one Indeed, the box (where the box indicates the 25th and 75th percentiles) and the whiskers (include extreme data points not considered outliers) of the distribution of the *full system* configuration shows a behaviour consistent with the one in Figure 5-3. More specifically, the box indicates that the region between 25th-75th percentile extends towards lower values; the whiskers that very low values can be reached. Finally, results clearly highlight that the *full system with distraction* configuration performs the worst since it has the higher median value (+4.92% with respect to *full system*) and both box and whiskers are shifted towards higher values with respect to the other two groups of drives.

This outcome is complementary with the one presented in Section 3.3.3.

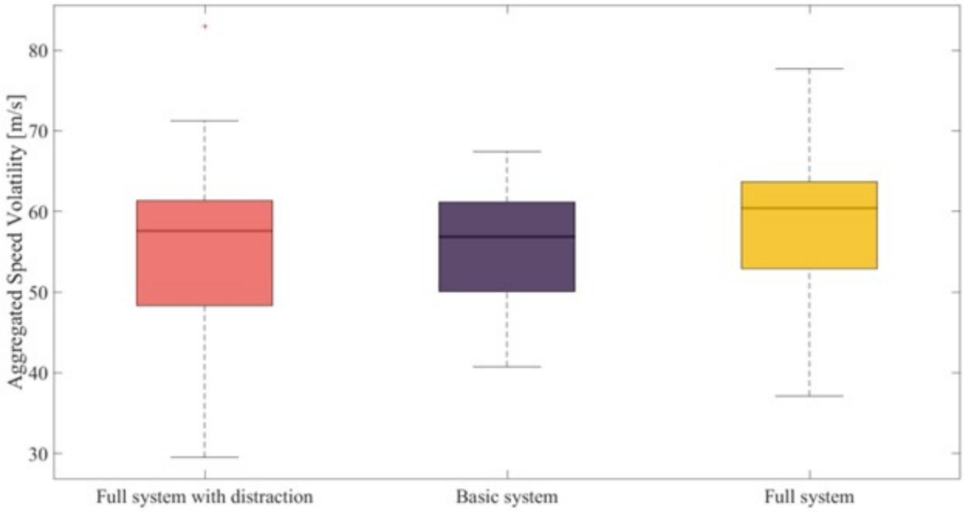

Figure 5-4 – Scenario A-I. Boxplot of the Aggregated Speed Volatility for the whole platoon. Red refers to fully system configuration, blue to basic system configuration and yellow to fully system with distraction configuration.

5.2.2. Scenario A-II

The scenario A-II involves the sub-route 2 (the motorway stretch connecting Alingsås to Vårgårda, see Figure 5-1) and the set-1 of values of car-following parameters in Table 5-1.

The first analysed KPI is the max deceleration. Boxplots in Figure 5-5 show the distribution of the maximum value of deceleration for each follower in the platoon. The outcome of Figure 5-5 shows that, on average, the *full system* configuration has the lowest median values, and the related distributions are less dispersed. This outcome suggests a more homogeneous and safe behaviour of followers. In this case, the *basic system* configuration presents comparable results to the *full system* in term of median values, but a more dispersed distribution (less homogeneous behaviour of followers). Furthermore, the increasingly dispersed trend of the distributions (1 is less dispersed than 2 and so on) indicates that the disturbances caused by the leader's behaviour tend to amplify in the platoon. The *full system with distraction performs*, on average, the worst since it has the larger dispersion and very high value of decelerations are reached; accordingly unsafe braking manoeuvres due to the sudden variation of the speed could occur.

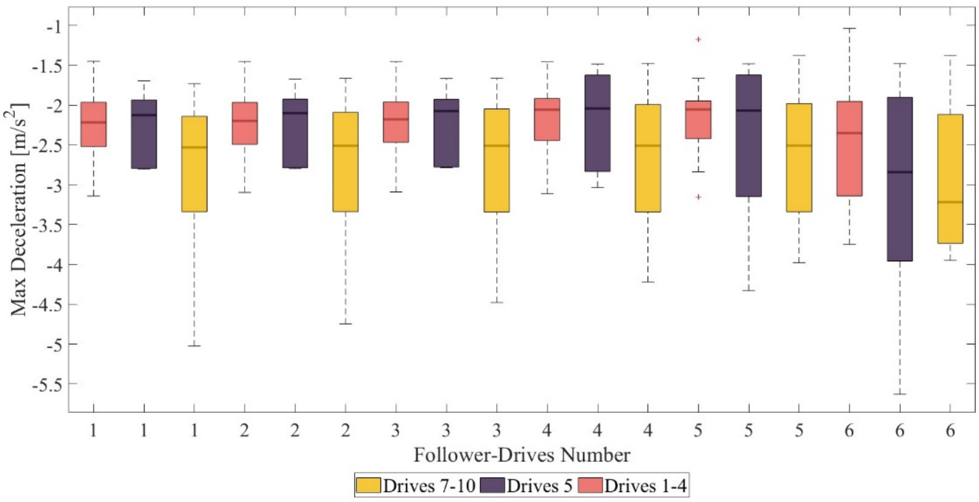

Figure 5-5 – Scenario A-II. Boxplot of the maximum deceleration of each follower i in the platoon (i = 1, …, 6). Red refers to fully system configuration, blue to basic system configuration and yellow to fully system with distraction configuration.

The second computed KPI is the standard deviation of the speed of each follower *i* in the platoon (*i* = 1, …,6). Related results are illustrated in Figure 5-6. They show that the *full system* and the *basic system* configurations present similar average trends, i.e., the lowest median values (for all followers). Regarding the whole distributions, the distributions with the *full system* are shifted towards very low values, while the ones related to the *basic system* are less dispersed. This outcome proves that the *full system* leads to the most stable behaviour of the followers. That is, minor fluctuations of the speed occur. Regarding the *full system with distraction* configuration, the related results present the worst performance in terms of median value (higher median value of standard deviation of speed), but the less dispersed distributions. In other word, they present a less stable behaviour of the followers in the platoon.

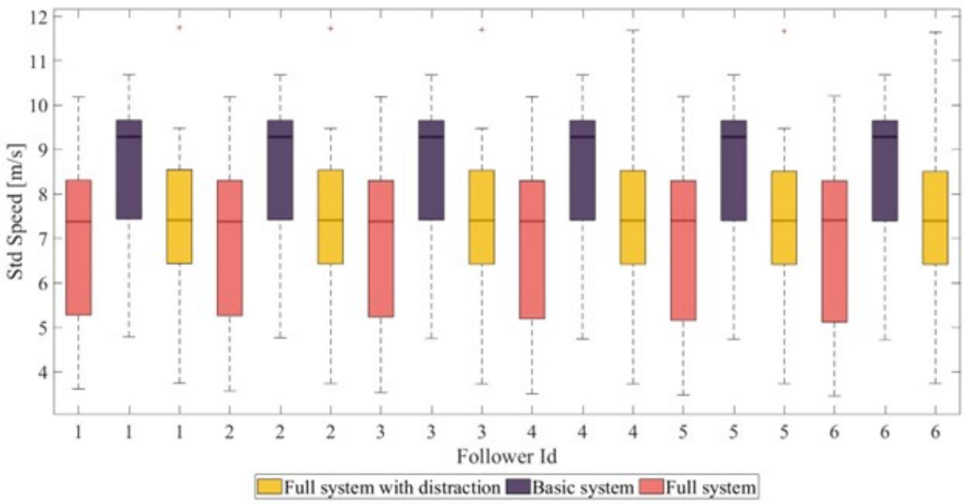

Figure 5-6 – Scenario A-II. Boxplot of the standard deviation of the speed of each follower i in the platoon (i = 1, …, 6) Red refers to fully system configuration, blue to basic system configuration and yellow to fully system with distraction configuration.

To link the variation in the speed data along the whole travelled path with the probability that a collision occurs, the Aggregated Speed Volatility is computed as defined in 0. Related distributions, referring to each drive group, are reported in Figure 5-7. The findings highlight that the *full system* and the *basic system* configurations led to a comparable median behaviour (very close median value). Considering the whole distribution, i.e., box and whiskers, the boxplots highlight that the *full system* results are shifted towards lower values with respect to the *full system with distraction*. Globally, these outcomes confirm that the *full system* and the *full system with distraction* result in the more stable behaviours of the followers. Finally, results clearly highlight that the *basic system* configuration provides the worst performance. Indeed, it has the higher median value (+31.36% with respect to the *full system*) and both box and whiskers are shifted towards higher values than the other two groups of drives.

This outcome is compliant with the one presented in Section 3.3.3.

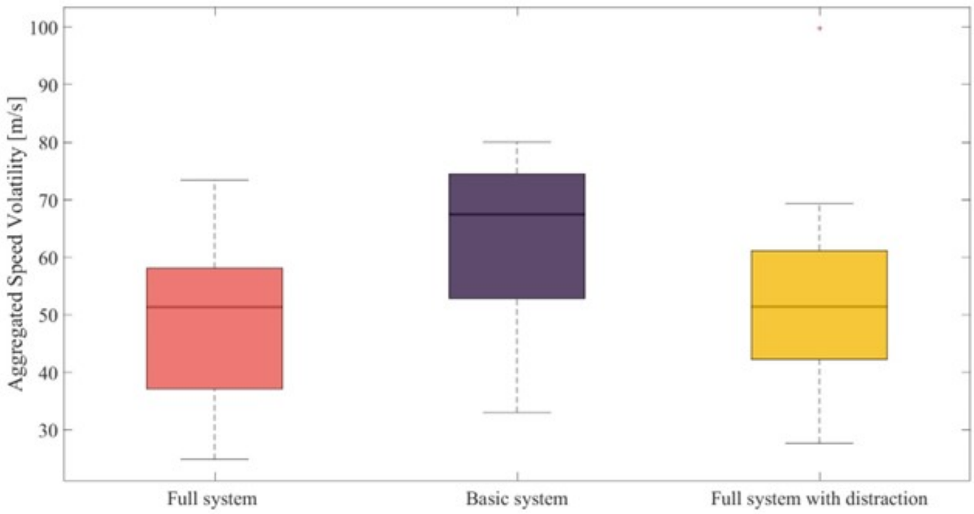

Figure 5-7 – Scenario A-II. Boxplot of the Aggregated Speed Volatility for the whole platoon. Red refers to fully system configuration, blue to basic system configuration and yellow to fully system with distraction configuration.

5.2.3. Scenario B-I

The scenario B-I involves the sub-route 2 (the motorway stretch connecting Vårgårda to Alingsås, see Figure 5-1) and the set-1 of values of car-following parameters in Table 5-1. For the sake of clarity, before moving into the analysis of scenarios B-I, the different drives and the car-following parameters are listed again below:

- Drives 1-4*: full system* (120 [s]– first (voice) and 30 [s] (sound)) - 21 complete drives available for each sub-route;
- Drives 5: very basic system without proactive automation and time budget info – 5 complete drives available for each sub-route;
- Drives 7-10: full system with distraction - 25 complete drives available for each sub-route;
- Car-Following parameters: a = 2.786 [m/s^2], b = 7.424 [m/s^2], h = 1 [s], d_{st} = 2.377 [m], τ = 1 [s].

The first analysed KPI is the max deceleration. Boxplots in Figure 5-8 show the distribution of the maximum value of deceleration for each follower in the platoon. The outcome proves that, on average, the cases with the *basic system* have the smallest median value; that is, smooth speed variations occur. The median values of the cases with the *full system* are not so different from the ones with the *basic system*, and the related distributions are the less dispersed. This indicates a more homogeneous behaviour of the followers. Finally, results in Figure 5-8 highlight that the *full system with distraction* performs the worst, since the related distributions have the lowest median value and the larger dispersion. Moreover, strong decelerations occur with the *full system with distraction*, which could lead to unsafe braking manoeuvres due to the sudden variation of the speed.

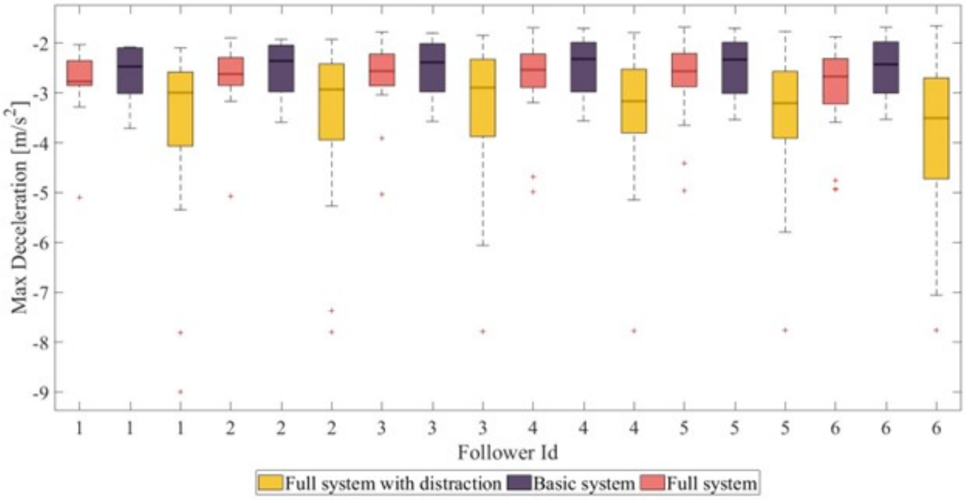

Figure 5-8 – Scenario B-I. Boxplot of the maximum deceleration of each follower i in the platoon (i = 1, …, 6). Red refers to fully system configuration, blue to basic system configuration and yellow to fully system with distraction configuration.

Regarding the standard deviation of the speed, the results in Figure 5-9 show that the *full system* configuration presents the lowest median values (for all followers). This outcome proves that with such configuration of the Mediator system the behaviour of the followers is, on average, more stable than in other drives. That is, minor fluctuations of the speed occur. It is worth noting that the *basic system* result in similar average values, but more dispersed distributions, to the *full system* configuration. In this scenario, the worst case in terms of average behaviour is represented by the *full system with distraction* configuration, which have the largest median values of standard deviation of speed. Moreover, even if the distributions of these latter drives are the less dispersed (more homogeneous behaviour), they are shifted towards high values of speed standard deviation; this implies a less stable behaviour of the followers in the platoon.

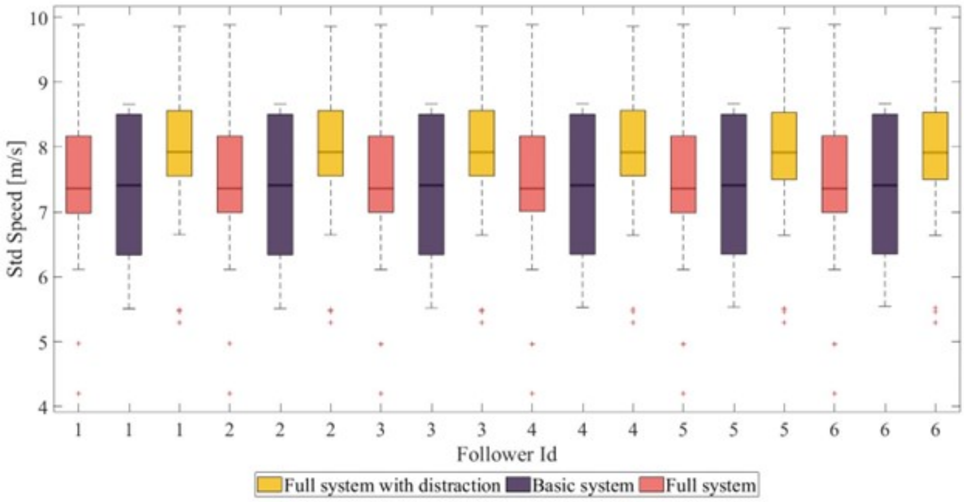

Figure 5-9 – Scenario B-I. Boxplot of the standard deviation of the speed of each follower i in the platoon (i = 1, …, 6). Red refers to fully system configuration, blue to basic system configuration and yellow to fully system with distraction configuration.

To link the variation in the speed data along the whole travelled path with the probability that a collision occurs, the Aggregated Speed Volatility is computed. Related distributions, referring to each drive group, are reported in Figure 5-10. The findings highlight that the *full system* and the *basic system* configurations led to a comparable distribution of the Aggregated Speed Volatility, with the latter having a slightly lower median value with respect to the former (- 1.23 %). Finally, results highlight that the *full* *system with distraction* has the worst performance since it has the higher median value (+8.28 % with respect to the *full system*) and both box and whiskers are shifted towards higher values with respect to the other two groups of drives.

This outcome complements that presented in Section 3.3.3.

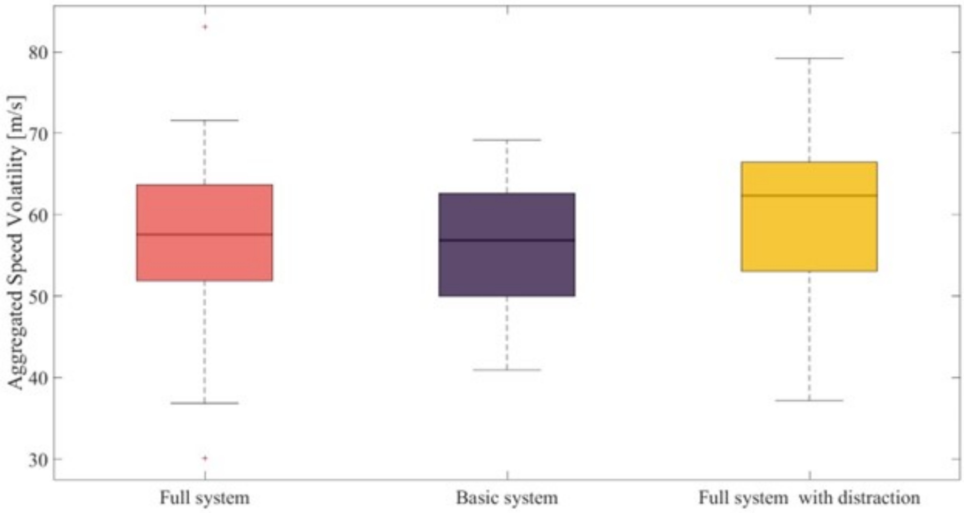

Figure 5-10 – Scenario B-I. Boxplot of the Aggregated Speed Volatility for the whole platoon Red refers to fully system configuration, blue to basic system configuration and yellow to fully system with distraction configuration.

5.2.4. Scenario B-II

The scenario B-II involves the sub-route 2 (the motorway stretch connecting Alingsås to Vårgårda, see Figure 5-1) and the set-2 of values of car-following parameters in Table 5-1. For the sake of clarity, before moving into the analysis of scenarios B-I, the car following parameters are listed again below:

- Car-Following parameters: a = 0.8 [m/s^2], b = 8 [m/s^2], h = 0.4 [s], d_{st} = 2.5 [m], τ = 0.4 [s].

The first analysed KPI is the max deceleration. Boxplots in Figure 5-11 show the distribution of the maximum value of deceleration for each follower in the platoon. The outcome of Figure 5-11 shows that, on average, the *full system* configuration led to the smallest magnitude of median values and the related distributions are the less dispersed. This outcome suggests a more homogeneous and safe behaviour of followers. In this case, the *basic system* and the *full system with distraction* provide similar results in term of median value of maximum deceleration. However, considering the whole distribution, the performance achieved with the *basic system* are the worst since they have the larger dispersion and very high value of decelerations are reached; accordingly unsafe braking manoeuvres due to the sudden variation of the speed could occur.

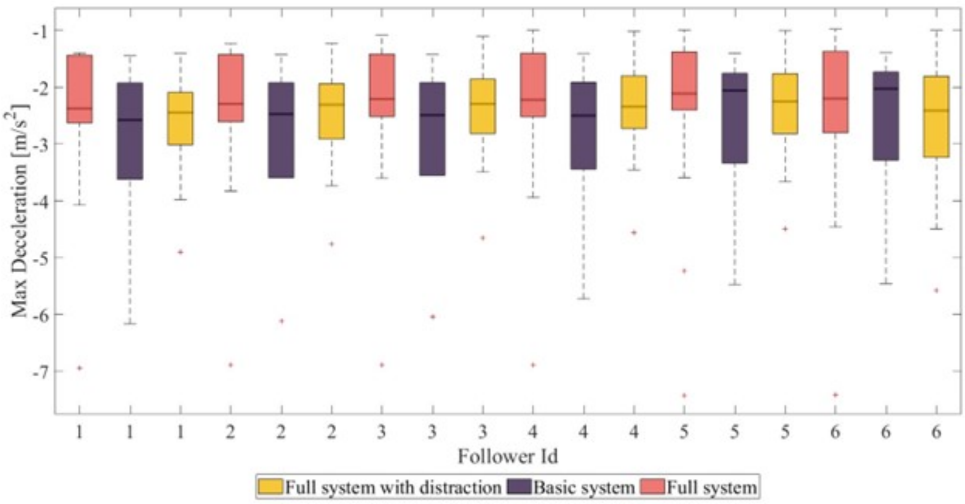

Figure 5-11 – Scenario B-II. Boxplot of the maximum deceleration of each follower i in the platoon (i = 1, …, 6). Red refers to fully system configuration, blue to basic system configuration and yellow to fully system with distraction configuration.

The second computed KPI is the standard deviation of the speed of each follower *i* in the platoon (*i* = 1, …,6). Related results are illustrated in Figure 5-12. They show that the *full system* and the *full system with distraction* present similar average trend, i.e., the lowest median values (for all followers). Regarding the whole distributions, the ones related to the *full system* are shifted towards very low values, while the ones related to the *full system with distraction* are the less dispersed. This outcome proves, above all, that with the *full system* the behaviour of the followers is, on average, the most stable. That is, minor fluctuations of the speed occur. Instead, regarding the cases with the *full system with distraction* configuration, they are characterised by the most homogeneous behaviour. In this scenario, the worst case in terms of average behaviour is represented by the *basic system*, which have the higher median value of standard deviation of speed; more generally, in this latter case distributions are shifted towards high values of speed standard deviation, which implies a less stable behaviour of the followers in the platoon.

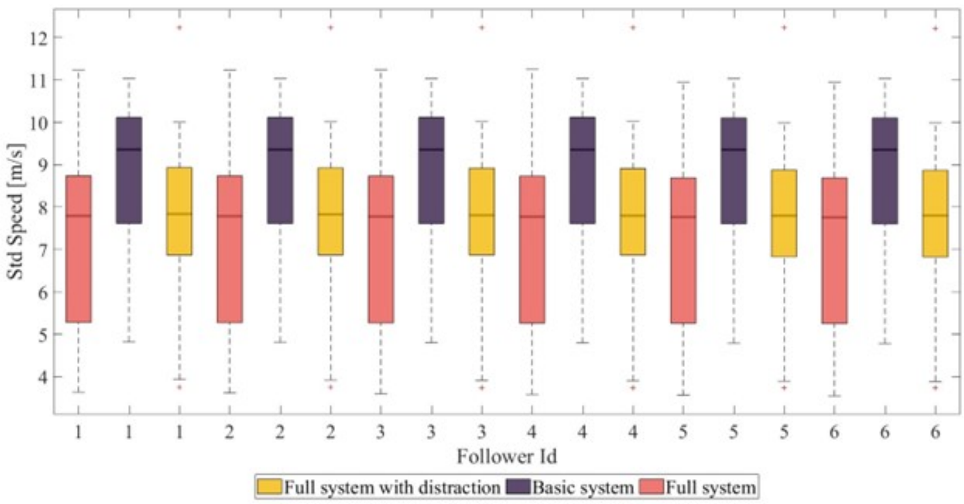

Figure 5-12 – Scenario B-II. Boxplot of the standard deviation of the speed of each follower i in the platoon (i = 1, …, 6). Red refers to fully system configuration, blue to basic system configuration and yellow to fully system with distraction configuration.

To link the variation in the speed data along the whole travelled path with the probability that a collision occurs, the Aggregated Speed Volatility is computed as defined in 0. Related distributions, referring to each drive group, are reported in Figure 5-13. The findings highlight that the *full system* and the *full system with distraction* led to a comparable median behaviour (very close median value). Considering the whole distribution, i.e., box and whiskers, the boxplots highlight that the ones related to the *full system* are shifted towards lower values with respect to the ones related to the *full system with distraction* Globally, these outcomes confirm that the *full system* and the *full system with distraction* configurations result in the more stable behaviours of the followers. Finally, results clearly highlight that performance with the *basic system* configuration are the worst since it has the higher median (+35.75 % with respect to the *full system* value and both box and whiskers are shifted towards higher values with respect to the other two drives groups.

This outcome is compliant with the ones presented in Section 3.3.3.

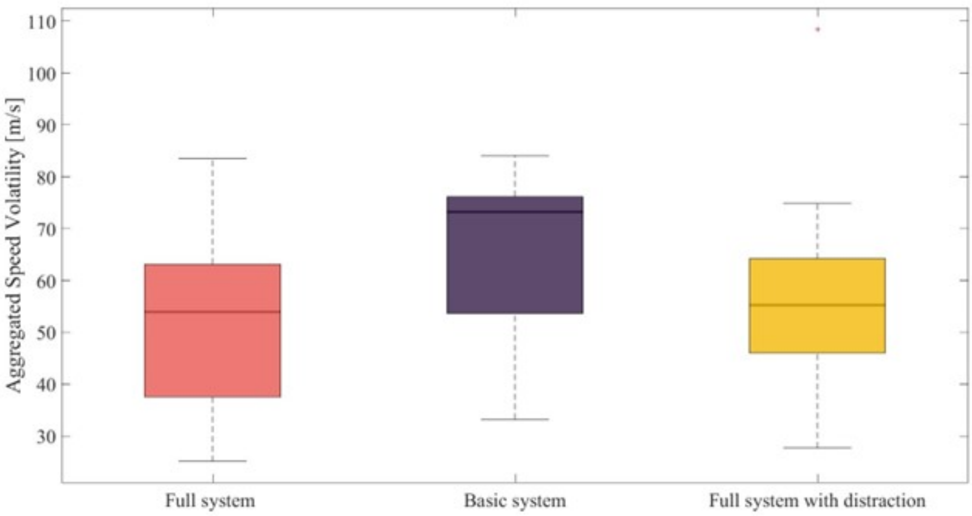

Figure 5-13 – Scenario B-II. Boxplot of the Aggregated Speed Volatility for the whole platoon. Red refers to fully system configuration, blue to basic system configuration and yellow to fully system with distraction configuration

5.3. Conclusions

To evaluate the impact of the Mediator system on driving behaviours of the followers, four scenarios were designed in the experiment involving two different types of drivers (representing different driving styles) and two sub-routes extracted from the complete field trial. Moreover, the analysis involves three different configurations of the Mediator system, namely *full system*, *basic system* and *full system with distraction.* To quantify the impact of the system, several KPIs were employed, namely the maximum deceleration, the standard deviation of speed and the Aggregated Speed Volatility.

Globally, the results prove that the *full system* configuration of the Mediator system performs the best: it leads to less intense fluctuations and smoother speed variations, thus determining a more stable behaviour of the entire platoon than the other system configuration. These results were confirmed also by the trend of Aggregated Speed Volatility, which links the variation in the speed data along the whole travelled path with the probability that a collision occurs. It is worth to note that this result is consistent with the fact that the *full system* configuration was characterised by the higher usage of the Pilot Assist. Indeed, human driver behaviour changes when following a vehicle equipped with PA systems; more specifically the uncertainty inherent in human driver behaviour is reduced (Zheng et al., 2020). Regarding the other configuration of the system, they were found to have different performance based on the analysed scenarios. Specifically, the *basic system* configuration performed better than the *full system with distraction* on route composed of heterogeneous segments with high and low-speed limit. Instead, the *full system with distraction* performs better when considering only extra-urban segments.

In summary, the impact of the Mediator on traffic congestion and instability is dependent on how it is implemented and used. According to the above discussion, the following conclusions can be drawn:

  - The *full system* configuration of the Mediator system outperforms the others in these scenarios and either assumed driving behaviour of surrounding vehicles
    - considering both extra urban and urban road conditions, this configuration has slight better performance with respect to the *basic system* configuration, while it outperforms the *full system with distraction* ì;
    - in only extra urban road conditions, this configuration clearly outperform the *basic system* and the *full system with distraction* ones
- the *full system* configuration of the Mediator system increases the utilization of the PA system
  - PA can reduce the likelihood of traffic crashes, can prevent sudden stops by reacting faster than drivers to changes in traffic conditions (so to improve traffic flow and prevent traffic congestion)
  - the usage of PA systems by an automated vehicle in a platoon of human-driven vehicles dampens stop-and-go waves (Stern et al., 2018), stabilizes flow (Ye & Yamamoto, 2019) and expands the portion of smooth driving (Cui et al., 2017).
- With the *full system* configuration, drivers tend to follow the advice of the mediator system more and better.
  - the Mediator system in this configuration can improve traffic stability and congestion by providing real-time information and promoting safe driving behaviour;
  - other configurations could create distractions and contribute to sudden changes in traffic flow, leading to instability on the road;

These conclusions highlight that the *full system* configuration of the Mediator system allows for a homogenizing effect on the behaviour of the following vehicles. This is due to the high usage of the PA and the compliance with the real-time information provided by the Mediator system. With more vehicles traveling at a similar speed, the flow of traffic is smoother. The advantages of a smooth traffic flow are the following:

- reduced stress and fatigue for drivers, improving comfort and reducing the likelihood of errors or crashes; this result is consistent with the ones showed in Chapter 2 and Chapter 3 of this deliverable;
- this results in less congested and more stable traffic flow.

To conclude, it is crucial to highlight two important aspects. Firstly, this study considers the interaction of the Mediator system with human drivers from various European countries, which is modelled by considering different driving styles. While further research is required, this finding represents an initial demonstration that the system can have positive effects in diverse contexts of application, namely, across different European countries. For instance, considering the extra urban road environment, the Mediator system could strongly reduce the Speed Volatility (about – 36 %) with respect to the case it is not available or is in a too simple configuration. On the other hand, it is imperative to emphasize that the results obtained are based on a limited dataset consisting of only seven experienced drivers who participated in an on-site examination under a specific experimental setting. Therefore, more comprehensive research is necessary to establish conclusive findings on the implications of the Mediator system on traffic flow.

5.4. References

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6. Safety assessment of Mediator system using expertise from aviation domain

In this Chapter a safety assessment of the Mediator system is performed using expertise from the aviation domain.

6.1. Scope

During a review, it was assessed that the safety assessment and determination of the safety benefits (expressed using KPIs) as done for the cases covered by D3.3, D3.4 and in Chapter 2 of this documents was done in ways similar to those used in aviation and also it was assessed that the safety assessments were performed correctly.

Therefore, this work has not been repeated and is therefore not described in this Chapter. Instead, a number of elements that affect safety that were not covered by D3.3, D3.4 and Chapter 2 of this document have been identified (see section 6.2).

A safety assessment of Mediator dealing with a reduction or deficit (a fault) in automated driving capabilities has not been performed, as Mediator cannot identify circumstances which the automated driving system is not able to deal with properly, and consequently Mediator is not able to advise the driver to take over control in this case.

6.2. Safety assessment of cases covered by D3.3, D3.4 and Section 2

This section identifies elements that affect safety that are not covered in the cases described in D3.3, D3.4 and Chapter 2 of this report. These elements are indicated *in italics.*

6.2.1. Mediator providing alerts in case of fatigue or distraction (D3.3 and D3.4 cases)

In the driving simulator studies covered by D3.3:

- Mediator keeps the driver (manual driving mode) in the loop (by using an audio-visual Trivia game and by notifications of upcoming hazards) when the driver becomes drowsy as detected by Mediator.
- Most participants expected an increase in road safety when driving with Mediator, due to decreased fatigue and distraction (which were the Key Performance Indicators).

For these safety benefits to be realised:

- The Mediator system must be available (no technical failures).
- The Mediator system must be turned on by the driver (driver trusts the system and accepts it)

In the in-the-road studies covered by D3.4:

- Mediator provides fatigue and distraction warnings in case of fatigue and distraction as detected by Mediator.
- From the interview an appreciation of the concept of distraction warnings was found. The questionnaire did not show a clear appreciation of the distraction warnings.
- There was no observable improvement in fatigue (which was the Key Performance Indicator) due to the warning.

For safety benefits in case distraction to be realised:

- *The Mediator system must be available (no technical failures).*
- *The Mediator system must be turned on by the driver (driver thrusts the system and accepts it)*

6.2.2. Mediator encouraging the use of automation (D4.1 Chapter 2 case and D3.4 case)

In the studies based on an open-access-dataset covered by D4.1:

The risk for a read-end crash under ACC is found to be much lower than the crash risk under manual control at the European level, as expressed by probability of a collision or speed volatility (KPIs).

In D3.4 for a vehicle without Mediator approximately 69% of drivers would be driving manually while distracted and automation was available, while for a vehicle with Mediator only 57% would do so. Thus, Mediator encourages automation usage (i.e. ,using Pilot assist when it is available), which would have positive impact on safety in terms of the time-to-collision and speed volatility.

For these safety benefits to be realised:

- The Mediator system must be available (no technical failures).
- The Mediator system must be turned on by the driver (driver trusts the system and accepts it)

6.2.3. Mediator initiating an automaton take-over in case of severe distraction (D3.4 case)

In the on-the-road studies covered by D3.4:

- At a certain critical level of distraction Mediator initiates an emergency take-over by the "automation" (specific SAE levels of driving automation is not mentioned).

For these safety benefits to be realised:

- The Mediator system must be available (no technical failures).
- The Mediator system must be turned on by the driver (driver trusts the system and accepts it)
- Driving automation of at least SAE level 3 must be available (see Chapter Appendix D for justification)

6.2.4. Results and discussion

For the safety benefits covered by D3.3, D3.4 and D4.1 to be realised, the Mediator system must be available (no technical failures), and the driver must thrust the Mediator system and turn it on.

6.3. Recommendations for the aviation domain

This section contains recommendation for the aviation domain based on expertise gathered about the driving automation during the course of the MEDIATOR project.

SAE level 2 of driving automation appears to be beneficial for safety in the automotive domain because it reduces workload, whereas in aviation, supervision of automation (which is equivalent to level 2) appears to be not always beneficial for safety because the pilot may be out of the loop.

It might be worthwhile for aviation to study whether aviation can learn from the way the automotive industry implements automation in these cases, in order to ensure that future aviation automation keeps the pilot sufficiently in the loop.

7. Effort required to develop a safe driver monitoring system

In this section the effort required to develop a properly functioning driver monitoring system is described.

A driver monitoring system must function properly in order to achieve safety benefits. This is further explained below.

A driver monitoring system is based on supervised learning, which is a form of Machine Learning.

Supervised learning is learning from labelled training data (e.g., pictures from dogs labelled as 'this is a dog'). In this case a deep neural network maps an input (e.g., a picture from a dog) to an output. The output (this is a dog, or this is something else) is compared with the label (this is a dog) and the weights within the neural network are adjusted accordingly.

In case of a driver monitoring system, the labelled data consist of physiological measurements of driver states with an indication whether the driver is fatigued, is not paying attention or is incapacitated.

7.1. Safety requirements of Mediator driver monitoring system

In order to achieve a certain safety benefit the Mediator driver monitoring system must be available, i.e., detect driver fatigue, detect that the driver is not paying attention and detect driver incapacitation.

To achieve the maximum safety benefit the availability of the driver monitoring system should be at least that of the driving automation, for example 99,9% or 99,99% per driving hour (this is based on failure rates of the components of the automated driving system being similar to failure rates of aircraft components which usually have failure rates of 1 per 1000 flight hours to 1 per 10000 flight hours).

In other words: the supervised-learning-based driver monitoring system must detect driver fatigue, detect that the driver is not paying attention and detect driver incapacitation with a success rate of 99,9% or 99.99% (again these figures are based on estimated failure rates of the components of the automated driving system using expert judgement).

To prevent the driver turning off the Mediator driver monitoring system due to being annoyed by false alarms, the false alarm rate should not exceed a certain threshold, for example 1% of all alarms. 1% is a common figure used in aviation.

In other words: the supervised-learning-based system must not generate false positives regarding driver fatigue, driver not paying attention and driver incapacitation at a rate higher than 1%.

7.2. Methods to ensure correctness

Ensuring correctness and completeness of the training dataset

Neural networks are not efficient learners. They need a lot of training data. Human beings often only need one example and an implicit transfer of prior experience.

The question is how can a training dataset be defined? In other words, how can the completeness and correctness of the training dataset be assured?

Challenges include:

- Every human being is different, so what is a representative set of human beings.
- Variance can cause an algorithm to model the random noise in training data, rather than the intended outputs.
- Bias can cause an algorithm to miss the relevant assumptions between attributes and target outputs.

The problem space (in the real world) must be travelled through in a Monte Carlo like way. The circumstances that have been encountered must be registered, allowing assessment of sufficient coverage of the problem space. Probably corner cases will need to be covered in more detail. This requires a lot of effort.

Methods for identification of bias and variance must be developed through an analysis of the features that are retained by the deeper layers of the neural network, which can be a form of explainability of the way a neural network is coming to its conclusions.

A scientific approach must be followed for the building up of expertise. Findings during developments should be studied, theories must be developed, and these theories must be tested and verified in practice.

Once it is known which datasets are needed, a repository of validated datasets should be developed.

This process is finished when the system performs satisfactorily, i.e., the driver monitoring systems detects fatigue, not paying attention and incapacitation with a success rate of 99,9% or 99,99% and does not generate false positives regarding detect driver fatigue, driver not paying attention and driver incapacitation at a rate higher than 1%.

Selecting the appropriate neural network

The question here is how can a neural network be identified that is able to give correct answers (after learning) for a certain training dataset?

For this a scientific approach must be followed for the building up of expertise. Findings during developments should be studied, theories must be developed, and these theories must be verified in practice with tests.

Once it is known which neural networks are needed, a repository of validated neural networks should be developed.

Using a structured development process

Once all the knowledge about the required datasets and neural networks has been built up, a structured development process should be defined based on this knowledge and be used for development to ensure that no errors are made when applying this knowledge.

7.3. Results and Discussion

It should be noted the driver monitoring systems already exist and are on the market, but it is unknown (at least to the consortium) what their availability and false alarm rates are.

In case a driver monitoring system with the high availability and low false alarm rate would have to be developed a representative labelled dataset is required. This dataset would be very large and would require a lot of effort to acquire.

Acquiring the dataset would take time. This means that such a driver monitoring system would not be available in short term. Also costs to develop such a driver monitoring system would have to be carefully considered.

And finally, regulations must be in place to approve such a system.

8. Concluding remarks

Mediator is a system that can recommend which driving mode is the safest in a specific driving context (the state of the driver, the vehicle, and the environment). In the current implementation, Mediator is a system that operates on top of existing support or automated features in vehicles. Therefore, Mediator, by itself, does not have a direct safety benefit, instead it can optimize and realize the overall safety potential of driving with or without automation.

In this report, we have evaluated the safety potential of the Mediator system as a facilitator for realizing the safety potential by selecting a real-world scenario of using adaptive cruise control (continuous mediation automated driving) to prevent rear-end crashes and improve car following behaviour. We made these choices because across all studies, we relied on experimental data from either the TI prototype vehicle or the simulator studies where adaptive cruise control (ACC), i.e., a continuous mediation system was used. The TI-prototype vehicle features a SAE Level 2 driving assistance system – Pilot Assist – where ACC is the equivalent subpart of PA used for longitudinal control of the vehicle. In fact, most production and prototypes of driving assistance and automated driving systems in the market today use ACC as a fundamental building block for longitudinal control. ACC is a manoeuvre-based function whose capability can increase or decrease based on the level of automation[8]. Because of this, ACC is already quite widely available in many cars within the EU. Further, numerous studies over the years have established the safety benefits of ACC. This allows us to build upon to the existing body of research to establishing how the Mediator system will support drivers to realize this safety benefit by evaluating it in an existing form of automation. Further, current industry trends are centred around motorway driving. Thus, by selecting this scenario, we can place the Mediator's safety potential in a compelling manner for both policymakers and automotive manufacturers.

Mediator is functionally designed for mitigating and counteracting degraded driver performance, in particular for our analysis – distraction. There is a need to ground this with observed, on-road data to understand its impact. In Chapter 3, a statistical analysis was performed on the TI prototype trials data conducted in Sweden where drivers were found to have marginally faster reaction times than without the Mediator system, confirming the findings of D3.4.

Further, an improvement in driving performance is seen when driving with Pilot Assist as compared to driving without it. The effect of improved driver performance means Mediator could facilitate a substantial reduction in predicted collision frequency as estimated in Chapter 2. This becomes more evident when the following distances are much smaller, and drivers have less time to react to unexpected manoeuvres of the lead vehicle. This emphasizes that if Mediator is present in a car with a properly functioning driver monitoring system and automation, a better performance in TTC and speed volatility is possible because of Mediator leverages the safety potential of automated driving and enabling safer manual driving. The implication on driver distraction is Mediator can handover control to the automated driving function when the driver is distracted or has a shorter following distance, thus contributing towards improving safety. Even when driving in fully manual mode, Mediator's functional specifications can support the driver to bring back attention to the driving task and thus making even manual driving safer. Another important implication of the statistical modelling using real-world data presented in Chapter 2 is that automation is not (at least not yet) the definitive solution for eliminating traffic crashes. This highlights the key role of Mediator to identify these situations where automation is likely to perform at worse than the human and transfer control in a safe, timely manner.

Further, we found that that Pilot Assist usage is higher on highways when Mediator is present in the vehicle and consequently larger following distance. There was a marginal effect (although significant)

[8] Society of Automotive Engineers (2021). J3016 Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles. p.7.

on distractions when Mediator became unavailable, possibly because drivers are searching for information from the Mediator system – resulting in an unintended distraction caused by the Mediator system. This effect is unlikely to lead to a higher safety critical situation as compared to driving without Mediator.

Four safety critical scenarios which the Mediator system could encounter was presented in D1.4 (see Figure 1 below). When Mediator is performing its function successfully, there would always be one driver (either human or automation) who is fit to drive – thus remaining in the green area of the plane. If the traffic context changes to where Mediator is in the yellow regions, the countermeasures are expected to mitigate the safety challenge, and avoiding the condition where both are unfit to drive. The results of the on-road study with the TI-prototype and computer simulations found that Mediator was able to resolve 99.9% of all situations (D3.2).

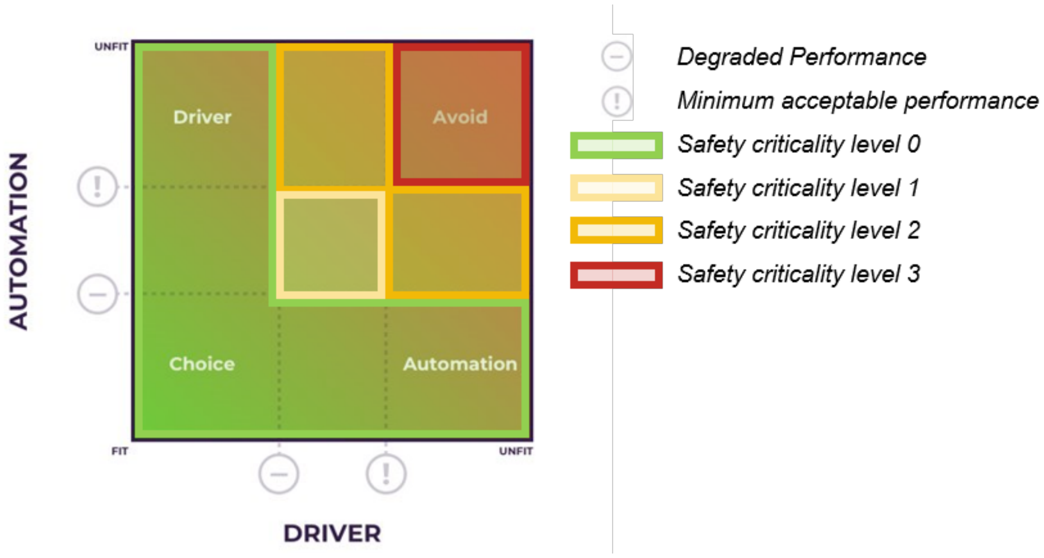

Figure 1 Driver/Automation fitness with safety critical events as presented in MEDIATOR report D1.4 (p.50)

If Mediator can resolve 99.9% of the tested scenarios, is Mediator the silver bullet to enable safe driving?

It depends. Manual driving has the potential to be safer than automated driving in certain contexts of car-following driving. For instance, if the human driver is defensive and maintains adequate margins, the frequency of collisions reduces by a substantial magnitude (Chapter 2). Automated driving can be safer when following distances are smaller. Crashes, as already discussed in section 2.4 happen to several reasons, many of which can potentially slip through Mediator's current functional and design specifications – for instance cognitive distraction or mismatch in expectations of the traffic context. Even though the results from D3.4 and Chapter 3 indicate only marginal effects of Mediator countermeasures on distraction, this is where Mediator's ability to fill in these gaps in degraded human performance with automation would be evident. While we cannot know for certain if 100% of all crashes will be avoided, we're confident that it has the potential to eventually achieve that target reduction.

Market penetration rate for new technology can be vary depending on various factors including cost, legal requirements, new vehicle registrations and other factors. For our analysis in Chapter 4, we assumed a market penetration rate based on the acceptance rate of the system (88%) – this could potentially be around the year 2044 based IIHS estimates for 85% market penetration of ACC[9]. This future version of Mediator could, in theory, detect all possible safety critical scenarios. We used this system for all rear-end collisions to estimate the savings by collisions prevented as: based on 2020's

[9] IIHS HILDI (2022) - Predicted availability of safety features on registered vehicles — a 2022 update. Retrieved from https://www.iihs.org/media/5cd18525-83b0-421e-8ee7-d0c3f9ebb262/vOHNyw/HLDI%20Research/Bulletins/hldi_bulletin_39-02.pdf

EU27 GDP, between 280 million (worst case) to 9.16 billion Euros (best case). Similarly, we would expect a similar reduction in the number of expected collisions and savings to the EU related to other crash types and configurations – a substantial saving to the EU citizens.

The impact of the Mediator system on the surrounding traffic flow were analysed in Chapter 5. To this end, data collected from TI in-vehicle prototype were employed to recreate the motion of such vehicle in a virtual simulation environment while surrounding vehicles were assumed to move according to Krauss car-following model. Followers with different driving styles were considered to evaluate the performance of the Mediator system in diverse contexts of application, namely, across different European countries. The outcome proves that the Mediator system, since it increases the utilization of the PA system (Chapter 3), allows to: homogenize the behaviour of the follower's vehicles; increase the reaction to variation in traffic conditions to improve traffic flow and prevent traffic congestion; improve traffic stability and congestion by providing real-time information and promoting safe driving behaviour; reduce stress and fatigue for drivers, improving their comfort and reducing the likelihood of errors or crashes (Chapter 2); less congested and more stable traffic flow. This finding represents an initial demonstration that the system can have positive effects in diverse contexts of application, namely, across different European countries.

In Chapter 6 we performed an analysis of the Mediator system and its potential in traffic safety from the aviation perspective. As such, there no standardized method within aviation for such an analysis – however the preferred approach is to break down the system into its logical components and evaluate it's intended functions. The key findings of this analysis are that based on the design specifications and functions of the Mediator system, it can realise the safety potential of automated driving if the automation or driving assistance system is within its operational design domain and if the driver monitoring system can correctly identify and interpret the human driver's current state. This analysis was performed for two scenarios, one for driver distraction and fatigue (which the MEDIATOR project sought to address) and a second, driver incapacitation (a scenario highlighted through experiences in the aviation domain). A key difference between the two is that Mediator's design can successfully, theoretically, mitigate distraction and fatigue in all levels of automation, however, for a safe stop when the driver is incapacitated, a higher level of automation (SAE level 3 and higher or Standby Mediation or higher) is required with a Minimum Risk Manoeuvre feature. As one of the core elements for Mediator is its driver monitoring system, Chapter 7 highlights the effort needed for training models for safe driver monitoring.

The statistical and simulation methods used in all chapters of this report can be applied to other driving contexts and driving systems. For instance, to estimate the frequency of rear-end collisions, we used a statistical method called Extreme Value Theory. This method is used extensively in other fields such as meteorology to predict the occurrence of rare, natural disasters. The application to traffic safety is relatively new and presents a benefit that likelihood of collisions for new technology can be estimated with relatively small amounts of data. While EVT can be used for safety benefit assessment, it requires a set of conditions that are representative of specific driving modes/styles in which we are interested. To validate such results, we may still need to reference aggregate crash statistics. EVT is not a 'silver bullet' and it still requires corroboration with other complementary methods and information. For example, it could complement the simulation analyses from Chapter 4 to extract safety indicators and their association with congestion from large scale simulations. With further research, EVT could, potentially, be run in real-time and included in the transition logic by incorporating historic data, driving context, and driver traits (D1.2).

Our analysis shows that Mediator can improve road safety, have a positive effect on congestion, and reduce the collisions societal costs in rear-end car following driving on highways. This potential is realized by Mediator's ability to choose, between human and automation, the best driver in each driving context. Thus, not only does Mediator facilitate realizing the safety potential of automated driving, but it also compensates for its inadequacy in some contexts by complementing with manual driving. The various driver state countermeasure implemented through Mediator can facilitate the manual driving to be safer and more defensive.

Appendix A Optimization problem to compute Brake Threat Number (BTN)

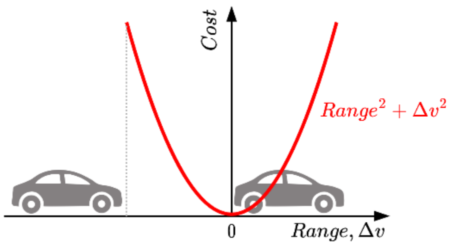

Figure A-1. The cost function to minimize is the squared range and relative velocity (Δv) to the vehicle ahead.

The cost function *C* to minimize was (Figure A-1):

$$C = r^2 + \Delta v^2 \quad \text{(A-1)}$$

where *r* is the range between the vehicles and Δ*v* is their relative velocity. The cost function *C* has a_{min} as the only parameter to optimize (minimize). That is, we wanted to find that acceleration value to avoid a collision (a^*_{min}) that takes full advantage of the available stopping distance. From the specific brake profile (which is different for the leader vehicle in simulation A and B), velocity (*v*), distance (*s*), and range (*r*) are obtained via numerical integration (trapezoidal method):

$$\min_{a^*_{min} \text{ in } [0, \infty)} C(a^*_{min}) = r^2(a^*_{min}, \ldots) + \Delta v^2(a^*_{min}, \ldots) \quad \text{(A-2)}$$

$$r(a^*_{min}, \ldots) = s_{leader}(t, t_d{=}0, a^*_{min}{=}a_{min}, \ldots) - s_{follower}(t, s_0{=}0, \ldots)$$

$$\Delta v(a^*_{min}, \ldots) = v_{leader}(t, t_d{=}0, a^*_{min}{=}a_{min}, \ldots) - v_{follower}(t, \ldots)$$

$$s(t, s_0, \ldots) = s_0 + \int (t, v(t, \ldots))$$

$$v(t, v_0, \ldots) = \begin{cases} v_0 + \int (t, a(t, \ldots)) & \text{if } v(t) \geq 0 \\ 0 & \text{Otherwise} \end{cases}$$

$$a(t, a_0, a^*_{min}, j, t_d) = \begin{cases} a_0 & \text{if } t \leq t_d \\ a_0 + j\,(t - t_d) & \text{if } t \leq t_d + t^* \\ a^*_{min} & \text{Otherwise} \end{cases}$$

$$\text{where } t^* = (a^*_{min} - a_0) / j$$

Appendix B Societal benefits in detail by country

B.1 Production loss

Hereby, based on productivity or income per capita, an estimate of the period of time victims are unable to work, the (loss of) productive capacity of a human being is valued. The mean productivity loss was calculated as the sum of future annual incomes considering life expectancy. This is called the human capital (HC) method, which is the basis of all damages-cost approaches. HC and the Willingness to pay (WTP, see B.2) are complementary approaches. Whereas the HC estimates the loss of productivity the WTP estimates the loss of quality of life. Both concepts contain the consumption loss, which is why a correction is necessary to avoid double counting. In almost all countries, the consumption loss is subtracted from the value of statistical life (VOSL), resulting in human losses. The consumption loss is then added to the production loss (known as "gross production loss"). Another factor is unpaid production losses, such as housework. For this purpose, surveys of time expenditure are used in combination with indicators of time costs (such as wages or costs of hiring staff). The loss of unpaid production can account for a significant percentage of total production loss: In the U.S., e.g., unpaid labour accounts for about 25 % of total production loss. Furthermore, in some countries (Australia, Germany, Switzerland and the USA) the "friction costs", i.e., the costs of hiring and training new employees, were estimated separately. These costs account for about 5 % of the production loss in Switzerland and the USA, and less than 1 % in Australia and Germany.

B.2 Human costs

International Guidelines propose the estimation of human costs by the Willingness to pay (WTP) method, which is described as the amount of money that people are willing to pay for a reduction in crash risk or to avoid undesired effects or receive a benefit (Willingness-to accept, Bahamonde-Birke, 2015). This approach measures the subjective value that society assigns to the protection of a human life, and it reflects the will and intentions of the population (Bahamonde-Birke, 2015).

According to Wijnen et al. (2016), human costs are assessed by WTP method. The determination of the value can either be done by stated (SP) or revealed preference (RP) method. With SP a concrete value is obtained by asking (in)directly how much people are willing to pay for safety provisions. In the context of a survey, respondents are presented with different alternatives, each with different attribute values, as part of a choice set. The goal is to choose the alternative that promises the highest benefit. Thus, respondents choose their preference in an implicit way. A disadvantage of the method is distortion and misinterpretation. Using RP methods, risk reductions are evaluated based on actual behaviour, e.g., purchasing behaviour related to safety precautions. A result of the WTP method is the value of statistical life (VOSL). VOSL does not refer to a concrete human life, but to an undefined statistical life, whose valuation is determined for situations with not certain but only low probability of occurrence (Bahamonde-Birke, 2015). VOSL consists of the valuation of human costs as well as the value of consumption loss. Another approach is to estimate human costs based on court-ordered compensation, legal values or use a rule of thumb. This indicates that human costs are estimated as fixed percentages of the total costs per fatality, serious injury and slight injury. Respectively, Wijnen et al. (2016) generated a list of studies and methods (Table B-1) that address this issue.

Table B-1 Value of a statistical life (VOSL), human costs per fatality, year for which VOSL has been estimated, and methods according to Wijnen et al. (2016).

	VOSL (mln US $ 2010)	Human costs per fatality (mln US $ 2010)	Base year VOSL	Method
High income countries (HIC)				
Australia		0.3	n.a.	Compensation payments
Austria	2.3	1.4	1998	WTP, EU-Value
Belgium	2.7		1009	WTP, EU-Value
Germany		0.04	n.a	Compensation payments
The Netherlands	2.9	2.4	2001	WTP, country-specific
Singapore		0.4	n.a	% cost fatality, rule of thumb
Switzerland	2.2		1998	WTP, EU-Value
UK		1.8	1991	WTP, country-specific
US		3.0	1990	WTP, country-specific
Low-middle income countries (LMIC)				
Cambodia		0.07	n.a	% cost fatality, rule of thumb
Indonesia		0.03	n.a	% cost fatality, rule of thumb
Laos		0.002	n.a	% cost fatality, rule of thumb
Myanmar		0.006	n.a	% cost fatality, rule of thumb
Philippines		0.02	n.a	% cost fatality, rule of thumb
Thailand		0.04	n.a	% cost fatality, rule of thumb
Vietnam		0.01	n.a	% cost fatality, rule of thumb

Note 1 n.a.=not available, WTP= willingness to pay

While in high income countries (HIC) using the WTP method, the share of human costs in the cost of a fatality is between 45 % and 77 %, in LMIC the share is much lower between 18 % and 28 %. The vast majority of countries include all types of crashes, meaning light and serious. One exception, according to Wijnen et al. (2016), is the Philippines, which includes only severe crashes. The USA measures the severity of crashes in terms of Quality Adjusted Life Years (QALYs), this builds in the implications of long-term consequences following a collision, an important societal issue, but without a direct cost for this purpose.

B.3 Property damage

The focus here is obviously on the damaged vehicle. The property damage is based on data from insurance companies. It should be emphasized, however, that not all damage is covered by insurance. Therefore, the vast majority of countries also include estimates of uncovered or unclaimed property damage. Different approaches are known for the calculations for uncovered or unclaimed damage in the different countries. On the one hand, the average property damage per crash - independent of the degree of severity - could be determined via the insurance companies. The number of crashes could be calculated based on police registration and assumptions. On the other hand, insurance pay-outs could be used as an indicator of property damage. Wijnen (2013) mentions that the range of unreported property damage percentage is large, e.g., 22 % (Austria) 50 % (Netherlands). The property damage incurred also includes damage to infrastructure. It is difficult to estimate how high the number of unreported damage events is. Taylor (1990) showed within a survey in the UK that only half of all damage events are reported to the insurance companies and that the average amount of damaging collisions is about three times higher than the number of reported crashes. In other words, property damage costs are probably significantly underestimated.

Table B-2 Expenditure of road crashes by OECD countries.

Country	Currency	Year	Fatalities	Severe Injury *	Slight injury	Property damage & other costs	∑	∑ in % of GDP
Argentina	USD	2017	9,192,24[a]	207,07[a]	19,64[a]		9,418,98[a]	1.7
Austria	EUR	2016	1,4 [b]	3,3 [b]	1,3 [b]	3,8 [b]	9,7 [b]	3.3
Australia	AUD	2006	9,9 [b]	10,3 [b]		6,9 [b]	27,1[b]	1.8
Belgium	EUR	2020	4,4 [b]	3,7 [b]	3,2 [b]	1,7 [b]	13 [b]	2.9
Canada	CAD	2018	17,62 [b]	10,91 [b]	3,87 [b]	16,317 [b]	40,74 [b]	2.1
Chile	USD	2020					5,5 [b]	2
Colombia	USD	2016					767 [a]	0.2
Czech Rep.	EUR	2020	710 [a]	440 [a]	661 [a]	1201 [a]	3 [b]	1.4
Denmark	EUR	2020	744 [a]	1226 [a]	95 [a]	1388 [a]	3,5 [b]	1.1
Finland	EUR	2020	572 [a]	518 [a]	306 [a]		1,4 [b]	0.4
France	EUR	2020	13,6 [b]	23,1 [b]	4,9 [b]	9,1 [b]	50,7 [b]	2.2
Germany	EUR	2020	3,32 [b]	6,97 [b]	1,5 [b]	19,68 [b]	31,47 [b]	0.9
Hungary	EUR	2021					4,1 [b]	3.4
Greece	EUR	2017	1,57 [b]	0,19 [b]	0,65 [b]	0,24 [b]	2,7 [b]	1.5
Iceland	EUR	2019	215,6 [a]			58, 49 [a]	274,09 [a]	1.3
Ireland	EUR	2018	363,5 [a]	475,2 [a]	177,9 [a]	124,2 [a]	1,1 [b]	0.4
Israel	ILS	2018	8 [a]	8,9 [a]	2050		14 [b]	1.2
Italy	EUR	2019	4,8 [b]	10,2 [b]	1,9 [b]		16,9 [b]	1
Japan								
Korea	USD	2020	1,26 [b]	4,61 [b]	3,02 [b]	2,51 [b]	22,11 [b]	1.3
Lithuania	EUR	2020	103,1 [a]	31,7 [a]	16,5 [a]		151,3 [b]	0.3
Luxembourg								
Mexico	USD	2020	8,1 [b]		11,6 [b]		19,7 [b]	1.6
Morocco	EUR	2020					2 [b]	2
Netherlands	EUR	2018	1,9 [b]	6,3 [b]	4,8 [b]	4,1 [b]	17,1 [b]	2
New Zealand	NZD	2018	5,37 [a]	551,700	30,800	0,8	5,7 [b]	1.8
Nigeria								
Norway[2]	EUR	2016				-	1,65 [a]	0.5
Poland	PLN	2018	6,85 [a]	37,48 [b]			44,9 [b]	2.1
Serbia	EUR	2017					272,1 [a]	0.7
Slovenia	EUR	2020	165,9 [a]	208,4 [a]	331,7 [a]	238,8 [a]	0,94 [b]	2.0
Spain[2]	EUR	2020					9,6 [b]	0.9

Country	Currency	Year	Fatalities	Severe Injury *	Slight injury	Property damage & other costs	∑	∑ in % of GDP
South Africa	ZAR	2017	68,7 [b]	34,8 [a]	22,9 [b]	35,7 [b]	162,05 [b]	3.5
Sweden[2]	EUR	2017					13,4 [b]	2.6
Switzerland[2]	CHF	2017					16,5 [b]	2.4
United Kingdom	GBP	2019					33 [b]	1.5
United States	USD	2010					242 [b]	1.6

*Note 1: 1=Human cost approach; 2= willingness-to-pay approach; [a]=million; [b]=billion; * includes hospitalized*

Table B-3. Total costs of road crashes and share in GDP according to Wijnen et al. (2013).

	Cost local currency	Unit	Currency	Year	Costs, US $ 2010	Share in GDP
High income countries						
Australia	17,849	Million	AUD	2006	13,596	1.7
Austria	10,158	Million	Euro	2004	13,223	4.3
Belgium	12,524	Million	Euro	2002	16,347	4.6
Germany	31,477	Million	Euro	2005	40,644	1.4
The Netherlands	12,469	Million	Euro	2009	15,074	2.2
Singapore	699	Million	SD	2011	749	0.5
Switzerland	14,078	Million	CHF	2003	10,038	3.2
UK	14,945	Million	Pound	2010	22,675	1
US	433,476	Million	USD	2000	542,303	4.3
Low-middle income countries						
Cambodia	66,064	Million	USD	2002	98,890	1.8
Indonesia	41,396	Billion	Rupiah	2002	15,289	2.9
Laos	47,383	Million	USD	2003	78,862	2.7
Myanmar	94,814	Million	MK	2003	423	3
Philippines	105,260	Million	P	2002	6,188	2.6
Thailand	115,932	Million	B	2002	8,818	2.1
Vietnam	11,034	Billion	D	2003	3,041	2

B.4 The Netherlands

The Dutch Institute for Road Safety Research (SWOV, 2023) provides information about the frequency of crashes in a public web tool. The frequencies of rear-end collisions in 2019 and 2020 are displayed in Table B-4. The data on rear-end collisions are combined with multiple collisions. According to the SWOV data department, the Dutch police did not always record the type of crash correctly from 2015 onwards, making the data set unreliable to some extent for the analysis of 2019 and 2020. More specifically, the crash type was often classified as “unknown.” To avoid underestimating the frequency, data for the “unknown” type are included in Table B-4.

Table B-4 Frequency of rear-end road traffic crashes in the Netherland involving personal injury by nature of crash and location.

	Injured		**Fatal**		**Material damage only**	
	Intra-urban	Extra-urban	Intra-urban	Extra-urban	Intra-urban	Extra-urban
2019						
Total	9	383		10	204	3,526
Rear-end	9	365		7	190	3,324
unknown	-	18		3	14	202
2020						
Total	11	201		1	130	1,595
Rear-end	11	182		1	118	1,465
unknown		19			12	130

B.5 Switzerland

According to the Swiss Federal Roads Office (ASTRA, 2021) statistics, rear-end collisions involving passenger car drivers as the primary initiator are the most common type of crash in 2021. Table B-5 shows the frequency for rear-end collisions with at least one passenger car whose driver is the main cause for the years 2019-2021 in Switzerland.

Table B-5 Frequency of rear-end collisions in 2019-2021 by crash severity in Switzerland

Year	Fatalities	Serious injury	Slight injury	Property damage	Total
2019	6	129	2,501	4,630	7,266
2020	5	95	1,975	3,779	5,854
2021	4	125	2,133	4,171	6,433

B.6 Austria

A total of 8,168 directional traffic crashes were documented by Statistiks Austria (2020) in 2019. Rear-end collisions belong to the crash category of directional traffic, which is described as collisions between road users (two or more) moving in the same direction without turning. 35 people died as a result of a crash in directional traffic. The evaluations also show that there were 11,245 people injured on Austrian roads as a result of this type of crash in 2019. Unfortunately, no information is available on the severity of the injury. In 2020, 6,031 directional traffic crashes were documented (Statistiks Austria, 2021). Among them, 27 people died as a result of a crash in directional traffic. In total, moreover, show that in 2019 there were 8,176 people injured on Austrian roads as a result of this type of crash. Information about property damage was unfortunately not reported.

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Appendix C Traffic flow simulations in detail

C.1 Car-Following Behaviour

The longitudinal motion of *i*-th follower (i = 1, …, 6) is modelled according to the car-following model proposed by Krauß (1998) under the assumption that humans can detect (by vision) the distance from the vehicle ahead and safely drive to keep a desired distance gap from it. The gap [m] among the *i*-th follower and its vehicle ahead can be described in terms of inter-vehicle distance as:

$$d_i(t) = p_i(t) - p_{i-1}(t) - l_{i-1} - d_{i,min}(t) \qquad \text{(C-1)}$$

where $p_i(t)$ [m] and $p_{i-1}(t)$ [m] are the relative positions of the front bumper of vehicles *i* and its predecessor *i-1*; l_{i-1} [m] is the length of the vehicle *i-1*; $d_{i,min}(t)$ [m] is the minimum safe distance, equal to $d_{i,min}(t) = d_{st} + h \cdot v_i$, being d_{st} [m] the standstill distance, h [s] the desired time-gap and v_i [m/s] the speed of the vehicle *i*.

The safe speed for the *i*-th follower can be finally expressed as:

$$v_{i,safe}(t) = -\tau \cdot b_i + \sqrt{(\tau \cdot b_i)^2 + v_{i-1}(t-\tau)^2 + 2 \cdot b_i \cdot g_i \cdot (t-\tau)} \qquad \text{(C-2)}$$

where τ is the reaction time of drivers; b_i [m/s^2] is the maximum deceleration of the vehicle *i*; v_{i-1} [m/s] is the speed of the vehicle *i-1*.

Since vehicles must respect the legal and performance constraints, the desired speed is computed as follows:

$$v\_(i, des)\ (t) = min\{v\_(i, safe)\ (t); v\_max; (v\_i\ (t-\tau) + a\_i\ )\} \qquad \text{(C-3)}$$

C.2 Key Performance Indicators

To compare the performance of the different Mediator system configurations on the surrounding traffic, the following KPIs are considered:

- Maximum decelerations [m/s^2];
- Standard deviation of speed [m/s];
- Aggregated Speed Volatility [m/s].

C.2.1 Maximum Deceleration

The maximum deceleration, expressed in [m/s^2], is the lowest value of deceleration observed in each single simulation run. Then, outputs of single runs (of each scenario) are aggregated for each follower *i* in the platoon. Boxplots are employed to display variation in samples of a statistical population without making any assumptions of the underlying statistical distribution.

This KPI is employed to spot unsafe braking manoeuvres due to the sudden variation of the speed. Indeed, this could lead to the propagation of disturbances in the motion of the followers and, hence, make their motion unstable.

C.2.2 Standard Deviation of Speed

The standard deviation of speed, expressed in [m/s], is a proxy of the magnitude of the speed variation along the journey. In this case, the standard deviation of the speed for all followers in each run is computed. Output of single runs (of each scenario) are aggregated for each follower *i* in the platoon. Then, boxplots are employed to display variation in samples of a statistical population without making any assumptions of the underlying statistical distribution. The lower the value, the more stable is the behaviour of the platoon as a less intense disturbance has been propagated.

C.2.3 Aggregated Speed Volatility

Speed Volatility [m/s] measures the driving variations that occur in the speed profile (Mahdinia et al., 2020). This study employs the mean absolute deviation of speed to quantify relative speed volatility. It shows variations in speed data by measuring the aggregated distance between each observation to their mean, and then aggregated across all followers in the platoon. Increases in speed volatility indicate an increase in collision probability. For the sake of brevity, this study reports the Aggregated Speed Volatility (ASV) aggregated over all the followers in the platoon only. Analytically, they are computed as:

$$ASV_i = \frac{1}{T}\sum_{t=0}^{T}\left|v_i(t) - \mu_{v,i}\right| \qquad \text{(C-4)}$$

$$ASV = \frac{1}{N}\sum_{i=1}^{N} ASV_i \qquad \text{(C-5)}$$

where $\mu_{v,i}$ is the mean value of the speed of the follower *i.*

For each simulation run, a value of ASV is obtained. Then, output of single runs (of each scenario) are aggregated. Again, boxplots are employed to display variation in samples of a statistical population without making any assumptions of the underlying statistical distribution.

C.3 Preliminary Analysis: behaviour of the TI in-vehicle prototype

A preliminary step involves the analysis of the behaviour of the TI in-vehicle prototype from real-world drives to spot unusual behaviours that could affect the obtained results.

C.3.1 Sub-Route 1

The first considered sub-route involves the mostly the motorway connecting Vårgårda to Alingsås. More specifically, as can be seen in Figure C-1, the sub-route goes from point A to point B and is about 30 [km] long. It is worth noting that the speed limit varies between 110 [km/h] and 40 [km/h]. Hence, even if all the segments of this sub-route are categorised as “highway”, they are heterogeneous in term of maximum allowed speed.

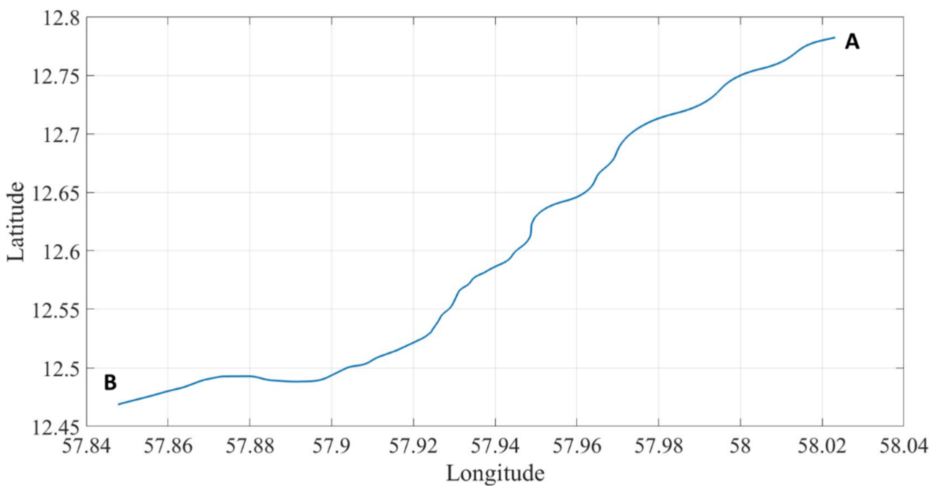

Figure C-1 – Considered highway sub-route, starting from point A, and ending at point B.

Speed trajectories of the different drives in the distance domain are reported in Figure C-2. Herein, the x-axis is the relative position of the vehicle along the route, expressed in [km]. The virtual TI in-vehicle prototype, starting from a speed of about 50-60 [km/h], travels for about 17 [km] on a motorway with a speed limit of 110 [km/h]. Then, the speed limit decreases down to 40 [km/h], to then increase up to 100 [km/h]. When between km 17.5 and km 22, i.e., in the road stretch with lower speed limits, it is worth noting that the virtual TI in-vehicle prototype reaches four times very low values of the speed (about 0 [km/h]). Speed trajectories plots and the travel time boxplot in Figure C-3**.** highlight that:

- in all drives, the virtual TI in-vehicle prototype is not compliant with legal speed limits, i.e., it travels with higher speeds;
- on average, the behaviour of the driver with the *full system with distraction* is more dispersed than in other two cases;
- on average, the drivers with the *full system with distraction* travel at higher speed compared to the other two cases;
- some non-smooth speed trajectories can be observed with both the *full system* and the *full system with distraction*.

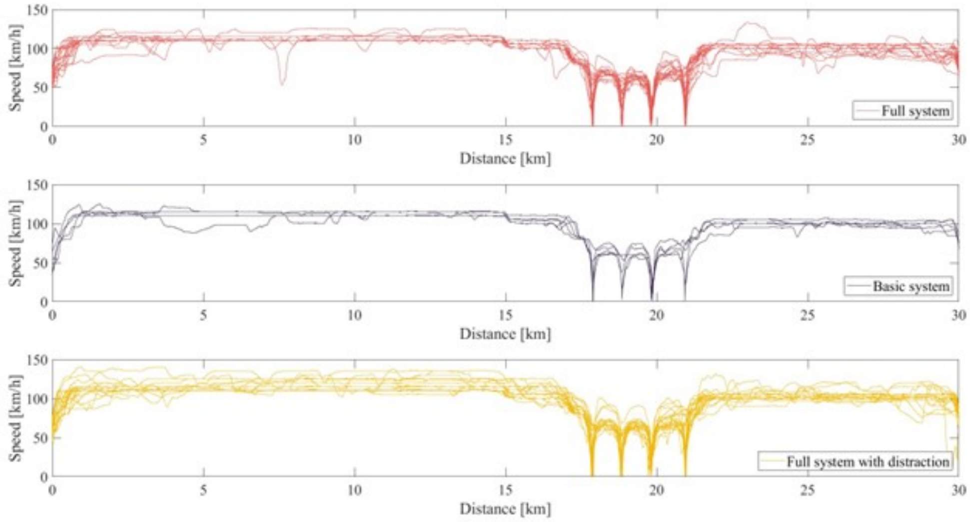

Figure C-2 – Sub-route 1. Distance-based speed profile of the virtual TI in-vehicle prototype. Top panel: fully system configuration; Middle panel: basic system configuration; Bottom panel: fully system with distraction configuration. Red refers to fully system configuration, blue to basic system configuration and yellow to fully system with distraction configuration.

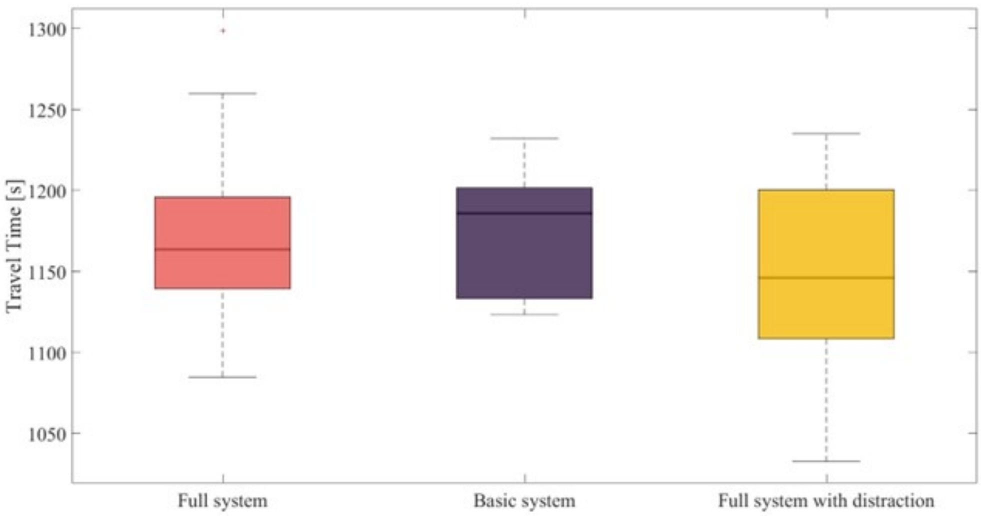

Figure C-3 – Sub-route 1. Travel time boxplot for fully system configuration, basic system configuration and fully system with distraction configuration.

A further effect of the Mediator system is related to the usage of the Pilot Assist (PA). It is worth noting that the proper investigation of such effects is outside the scope of this traffic flow analysis. The usage of the PA is here reported to link it with the obtained results. Indeed, the driving behaviour of vehicles equipped with automated driving systems is expected to be more standardized than that of human-driven vehicles with no automation (Tani et al., 2021). The boxplots in Figure B-4**.** show the percentage of space travelled with the PA with respect to the total travelled distance. The highest usage is found with the *full system* configuration. The *basic system* and the *full system with distraction* have comparable results in terms of median value, but the distribution of the *full system with distraction* is less dispersed (more homogeneous behaviour). This outcome is consistent with results shown in Figure 3-3 of Section 3.3.2. This further result confirms that the Mediator system, when in an appropriate configuration, encourages drivers to use the PA system when it is available and within its operation conditions, increasing automation usage (which is proven to be safer, see Section 2).

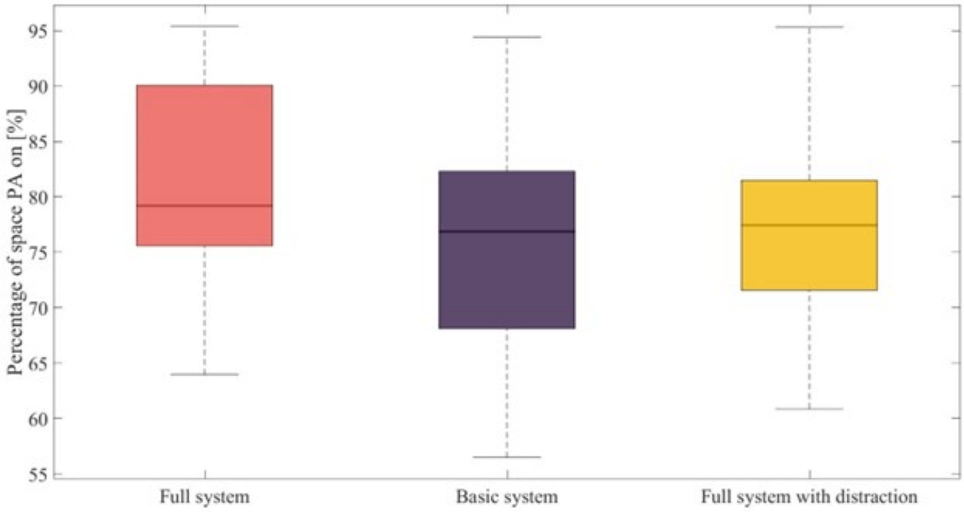

Figure C-4 – Sub-route 1. Boxplot of the usage of Pilot Assist. Percentage of space travelled with the Pilot Assist with respect to the total travelled distance. Red refers to fully system configuration, blue to basic system configuration and yellow to fully system with distraction configuration.

C.3.1 Sub-Route 2

The second considered sub-route involves the motorway connecting Alingsås to Vårgårda. More specifically, as can be seen in Figure C-5, the sub-route goes from point C to point D and is about 19 [km] long. The speed limit, in this case, is equal to 100 [km/h].

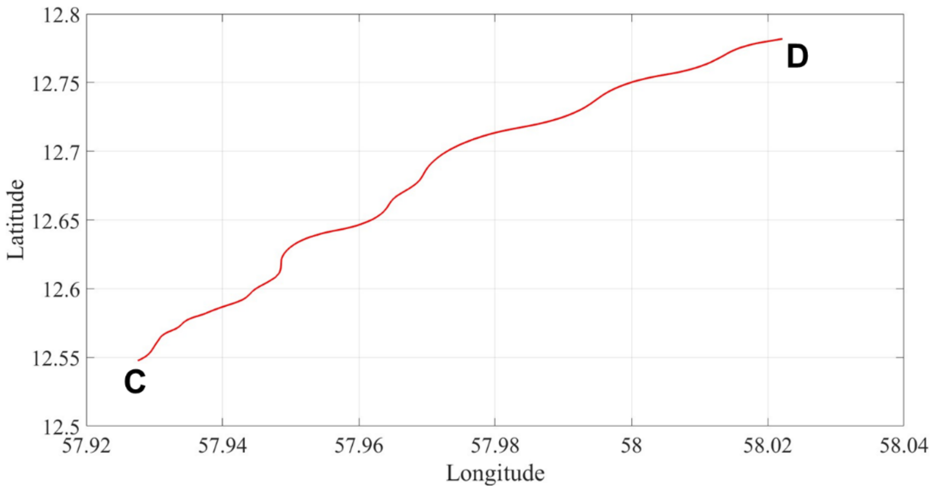

Figure C-5 - Considered highway sub-route, starting from point C, and ending at point D.

Speed trajectories of the different drives in the distance domain are reported in Figure C-6. Herein, the x-axis is the relative position of the vehicle along the route, expressed in [km]. The virtual TI in-vehicle prototype, starting from a speed of about 50-60 [km/h], travels for about 18 [km] on a motorway with a speed limit of 100 [km/h]. Speed trajectories plots and the travel time boxplot in Figure C-7**.** highlight that:

- in all drives, the virtual TI in-vehicle prototype is not compliant with legal speed limits, i.e., it travels with higher speeds;
- on average, the behaviour of the driver with the *full system with distraction* is more dispersed than the other two cases;
- on average, the drivers with the *full system with distraction* travel at higher speed compared to the other two cases;
- some non-smooth speed trajectories can be observed with both the *full system* and the *full system with distraction*.

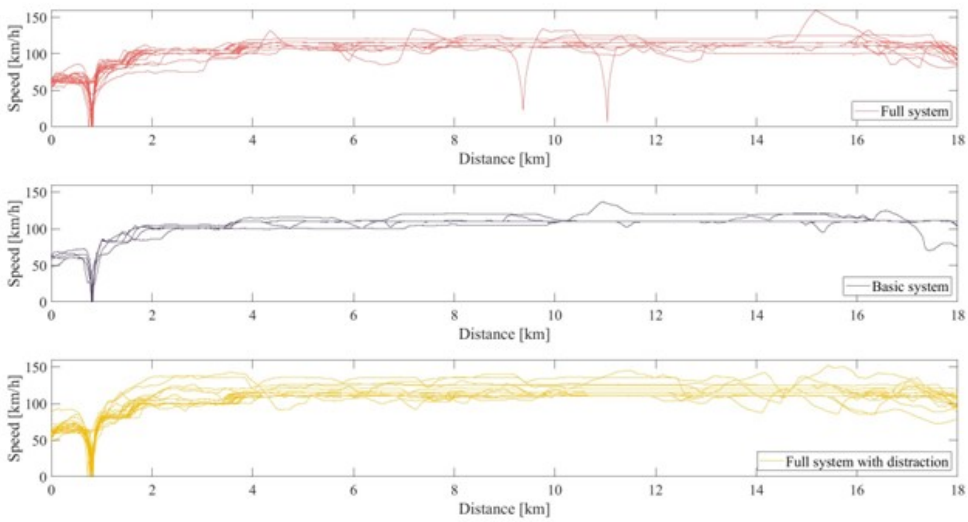

Figure C-6 – Sub-route 2. Distance-based speed profile of the virtual TI in-vehicle prototype. Top panel: fully system configuration; Middle panel: basic system configuration; Bottom panel: fully system with distraction configuration. Red refers to fully system configuration, blue to basic system configuration and yellow to fully system with distraction configuration.

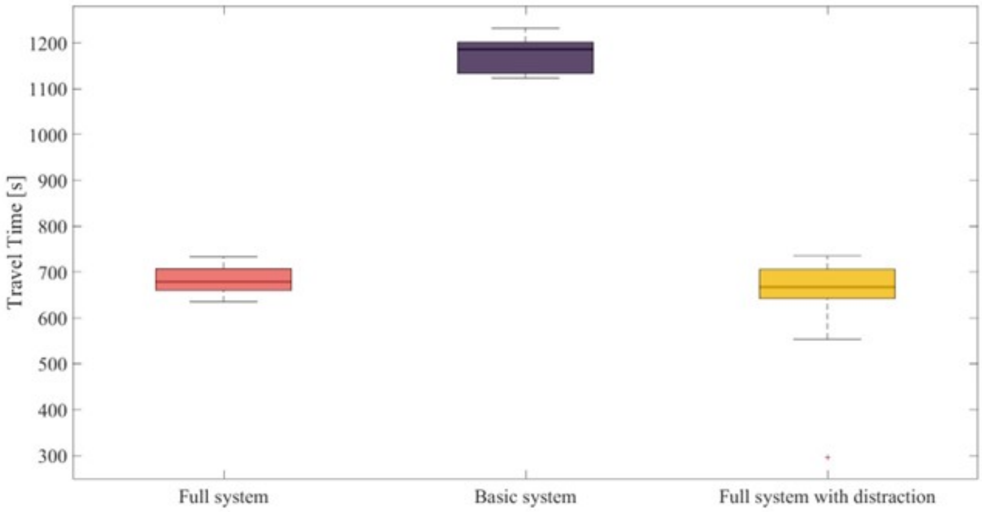

Figure C-7 – Sub-route 2. Travel time boxplot for fully system configuration, basic system configuration and fully system with distraction configuration.

Regarding the usage of the PA, the boxplots in Figure C-8**.** show the percentage of space travelled with the PA with respect to the total travelled distance. The highest usage is found with the *full system*. The *full system with distraction* and *basic system* have comparable results in terms of median value, but the distribution of the *basic system* is less dispersed (more homogeneous behaviour). This outcome is, again, consistent with results showed in Figure 3-3 of Section 3.3.2. This further result confirms that the Mediator system, when in an appropriate configuration, encourages drivers to use the PA system when it is available and within its operation conditions, increasing automation usage (which is proven to be safer, see Chapter 2).

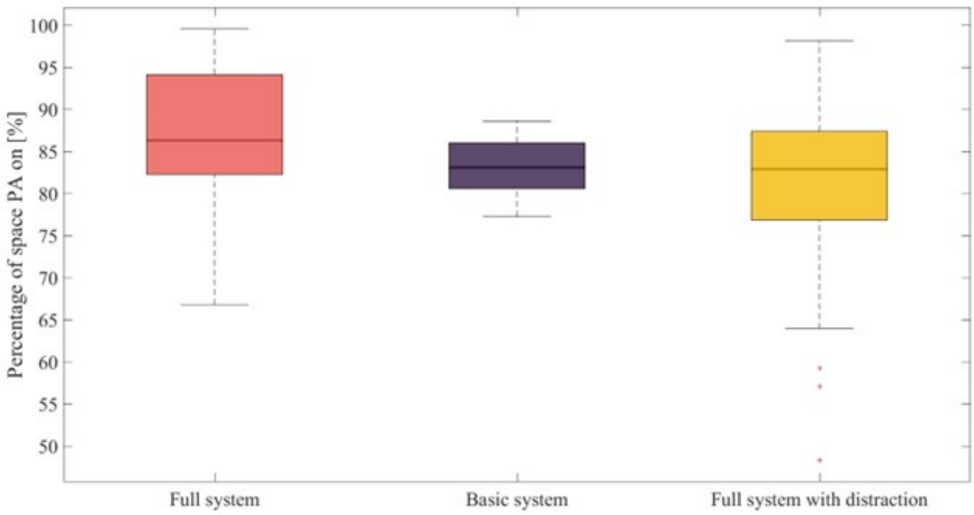

Figure C-8 – Sub-route 2. Boxplot of the usage of Pilot Assist. Percentage of space travelled with the Pilot Assist with respect to the total travelled distance. Red refers to fully system configuration, blue to basic system configuration and yellow to fully system with distraction configuration.

Appendix D Safety benefits of additional applications of the Mediator system

In this section a safety assessment is performed of additional applications of the Mediator system and the potential safety benefits are identified. These applications were not considered in the other work performed within the MEDIATOR project.

Additional applications considered are:

- The case of Mediator initiating an automation take-over in case of severe distraction (as also considered in D3.4 but without distinguishing between SAE levels of driving automation 0 to 5, or in case of incapacitation, distinguishing between SAE levels of driving automation 0 to 5
- The case of Mediator advising an automation activation or take-over in case of fatigue, distinguishing between SAE levels of driving automation 0 to 5.

The reasoning behind considering these applications is as follows:

Safety of baseline vehicle and driver

It is assumed that the vehicle is properly designed (for safety).

It is also assumed that with:

- Basic physical and mental fitness
- An adequate vehicle-driver interface
- An adequate level of training
- Absence of the following factors that may compromise safety:
    - Driver not paying attention (due to physical or mental distractions) (no task performance)
    - Driver incapacitation (no task performance)
    - Driver fatigue (increases task error rate)
    - Driver being reckless (due to driver character) (wrong decisions)
    - Driver being angry or frustrated (wrong decisions)
    - Drivers feeling time pressure (wrong decisions)

the dynamic driving tasks as performed by the driver are performed properly.

Driver errors and mitigation by driving automation and Mediator

In practice the driver does not always pay attention, gets fatigued, gets incapacitated and takes wrong decisions.

Driving automation mitigates some of these driver errors. This is further explained in the section Appendix D for SAE Levels of driving automation 0, 1, 2, 3, 4 and 5.

Driving automation is not always turned on though when within the ODD. This means that the mitigation for these driver errors is not working.

The use of Mediator could improve this situation:

- If the driver monitoring system from Mediator detects the driver is getting fatigued, Mediator proposes the driver to turn on the driving automation,
- If the driver monitoring system from Mediator detects the driver has become incapacitated, or detects severe distraction, Mediator turns on the driving automation.

This is further explained in Chapter D.1 for SAE levels of driving automation 0, 1, 2, 3, 4 and 5.

Note

Mediator cannot mitigate the safety effects of wrong decisions as Mediator is not able to identify wrong decisions such as:

- Overtaking from the right
- Cutting another vehicle off
- Not stopping for a red traffic light
- Not giving way
- Entering a curve with too high speed
- Overtaking when there is too little room (e.g., using the lane of the opposite direction)
- Keeping insufficient distance for braking to the vehicle in front

However, the driving automation itself would be able to detect wrong decisions (and alert the driver) when within the ODD. This is outside the scope of Mediator though.

Definitions

Two definitions are taken over from D1.1 here for readability:

Dynamic Driving Task - The Dynamic Driving Task (DDT) includes all tasks required to operate a vehicle in on-road traffic.

Operational Design Domain - Each level of driving automation is designed to work in specific conditions referred to as the Operational Design Domain (ODD). The ODD is defined as 'the specific conditions under which a given driving automation system or feature thereof is designed to function, including, but not limited to, driving modes. An ODD may include geographic, roadway, environmental, traffic, speed land temporal limitations.

D.1 Mediator initiating an automation take-over in case of severe distraction or incapacitation, and advising an automation take-over in case of fatigue

SAE level 0 of driving automation

Which tasks does the level 0 driving automation perform

These driver support features provide warnings (e.g., blind spot warning, lane departure warning) and momentary assistance (e.g. advanced emergency braking) when a perception error has been made.

Purpose of the level 0 driving automation

Correct potential driver perception errors.

Examples of level 0 driving automation

Present on many current vehicles:

Examples of warnings:

- Blind spot warning – provides a warning when there is a vehicle in the blind spot of the driver (potential perception error)
- Lane departure warning – provides a warning when the vehicle leaves the lane without using a turn signal (potential perception error)
- Distance warning (potential perception error) – provides a warning when there is insufficient distance for braking to the vehicle in front.
- Speed limit warning (potential perception error) – provides a warning when the speed limit is exceeded.

Examples of momentary assistance:

- ABS – prevents slipping of the wheels and the consequent degradation of braking performance in case of too hard braking by the driver given certain road surface conditions (potential perception error of road surface conditions)
- ESP – prevents (to a limited extent) loss of control of the car in case of turns that are taken with too high speed given certain road surface conditions (potential perception error of road surface conditions of turn radius
- Advanced emergency braking (e.g., city safety) – brakes maximally in case of object in front of car when moving at low speed (perception error of driver of other road user)

Driver responsibilities

The driver must always perform all driving tasks.

Operational Design Domain

Most level 0 driving automation is intended to operate in all circumstances. The lane departure warning only operates when there are lane markings.

Safety benefits of Mediator in case of driver fatigue

If driver fatigue is detected by the Mediator driver monitoring system => if elements of the level 0 driving automation are turned off, the driver is advised by Mediator to turn them on.

There is a safety benefit if:

- The Mediator driver monitoring system is available.
- Elements of the level 0 driving automation were turned off, and these elements are available.

The safety benefits per turned off and available element of the level 0 driving automation are:

- Blind spot warning – not overlooking a vehicle that is located in the blind spot.
- Lane departure warning - not leaving the lane accidentally.
- Distance warning - keeping insufficient distance for braking to the vehicle in front.
- Speed limit warning – not entering a curve with too high speed.
- ABS – maximum braking performance available when needed.
- ESP – preventing loss of control of the car in turns that are taken with too high speed.
- Automatic emergency braking - Not overlooking and hitting a road user or object in front of the vehicle.

False alarms of the Mediator driver monitoring system may result in the driver turning off the Mediator driver monitoring system and thus negating the safety benefit.

Safety benefits of Mediator in case of severe distraction or incapacitation

If severe distraction of driver incapacitation is detected by the Mediator driver monitoring system => there is no automation that Mediator can activate to cope with this. Activating the emergency braking system could lead a collision with the following vehicle and would therefore not be acceptable.

Mediator can provide a warning though. If there is a passenger on board he/she can try to take over the steering and possibly (although this requires more time) remove the foot of the driver from the gas pedal.

False alarms of the Mediator driver monitoring system may result in the driver turning off the Mediator driver monitoring system and thus negating the safety benefit.

SAE level 1 of driver automation

Which tasks does the level 1 driving automation perform

These driver support features provide steering support (lane centring) OR brake / acceleration (adaptive cruise control) support.

Purpose of the level 0 driving automation

Improve safety by reducing workload (and preventing fatigue).

Examples of level 1 driving automation

Present on many current vehicles:

- Lane centring
- Adaptive cruise control

Driver responsibilities

The driver must always perform the perception and decision-making sub-tasks of the steering, braking and acceleration tasks and must take over the action sub-task of the steering, braking and acceleration tasks when

- He/she perceives the circumstances will get outside the ODD (see * below)
- When the driving automation detects system degradation and alerts the driver (see *** below)

Operational Design Domain

- On the highway
- Adequate lane markings
- Good visibility

The driver must detect the following circumstances (because they are outside the ODD) (*)

- On the shoulder of the highway, on exits of the highway, when merging onto the highway, at intersections of the highway
- Other roads than a highway
- When lane markings are poor
- In case of bad visibility due to bad weather
- At construction zones
- When unusual object on the road (e.g., pieces of wood, cardboard, fallen tree, tree branches, animals, fallen road sign, fallen telephone poles, flooding, land slide, volcanic lava, spinning cars)
- Holes in the road
- When there is a tornado in front
- When there is an emergency vehicle approaching
- In case of technical failures such as blown tyre, loss of engine power

Driving automation detects system degradation and alerts the driver (***)

- Camera or radar sensors covered, obstructed or damaged.
- System failures

Steering support

Safety benefits of Mediator in case of driver fatigue

If driver fatigue is detected by the Mediator driver monitoring system => Mediator cannot advise to turn on the lane centring system as Mediator cannot determine that the vehicle is within the ODD.

Mediator can provide a warning of driver fatigue to the driver though.

False alarms of the Mediator driver monitoring system may result in the driver turning off the Mediator driver monitoring system and thus negating the safety benefit.

Safety benefits of Mediator in case of severe distraction or incapacitation

If severe distraction or driver incapacitation is detected by the Mediator driver monitoring system => Mediator cannot instruct to turn on the lane centring system as Mediator cannot determine that the vehicle is within the ODD. Even if it would turn on the lane centring system the vehicle would not be brought to a standstill and would eventually collide with something. S

Mediator can provide a warning though. If there is a passenger on board he/she can try to take over the steering and possibly (although this requires more time) remove the foot of the driver from the gas pedal. Or the driver may just in time resume the steering and braking and acceleration tasks in case of severe distraction.

False alarms of the Mediator driver monitoring system may result in the driver turning off the Mediator driver monitoring system and thus negating the safety benefit.

Brake / acceleration support

Safety benefits of Mediator in case of driver fatigue

If driver fatigue is detected by the Mediator driver monitoring system => Mediator cannot advise to turn on the adaptive cruise control as Mediator cannot determine that the vehicle is within the ODD.

Mediator can provide a warning of driver fatigue to the driver though.

False alarms of the Mediator driver monitoring system may result in the driver turning off the Mediator driver monitoring system and thus negating the safety benefit.

Safety benefits of Mediator in case of severe distraction or incapacitation

If severe distraction or driver incapacitation is detected by the Mediator driver monitoring system => Mediator cannot instruct to turn on the adaptive cruise control as Mediator cannot determine that the vehicle is within the ODD. Even if it would turn on the adaptive cruise control the vehicle would eventually collide with something or leave the road as no steering is performed.

Mediator can provide a warning though. If there is a passenger on board he/she can try to take over the steering and possibly (although this requires more time) remove the foot of the driver from the gas pedal. Or the driver may just in time resume the steering and braking and acceleration tasks in case of severe distraction.

False alarms of the Mediator driver monitoring system may result in the driver turning off the Mediator driver monitoring system and thus negating the safety benefit.

SAE level 2 of driver automation

Which tasks does the level 2 driving automation perform

The driving automation executes the steering (lane centring), braking and acceleration (adaptive cruise control) tasks when turned on.

Purpose of level 2 driving automation

Improve safety by reducing workload (and preventing fatigue).

Driver responsibilities

The driver must always perform the perception and decision-making sub-tasks of the steering, braking and acceleration tasks and must take over the action sub-task of the steering, braking and acceleration tasks when

- He/she perceives the circumstances will get outside the ODD (see * below)
- The driving automation detects that the circumstances will get outside the ODD and alerts the driver (see ** below)
- When the driving automation detects system degradation and alerts the driver (see *** below)
- Depending on the technical implementation hands-free driving is allowed or the driver must keep his/her hands on the steering wheel.

Operational Design Domain

E.g.

- On the highway
- With adequate lane markings
- In good visibility

The driver must detect the following circumstances (because they are outside the ODD) (*)

Construction zones (because the driving automation does not steer to avoid construction zones).

Unusual objects or situations on the road (the driving automation does not have AI to detects these):

The driving automation detects the following circumstances and alerts the driver (because they are outside the ODD (**)

- Limited intersections such as railroad crossings or pedestrian crossings
- Traffic control devices such as stoplights or stop signs.
- A road shoulder or service drive
- Highway exits (because after exiting steering is required)
- Merging into traffic (the system cannot merge into traffic)
- Poor lane markings
- Lane markings obscured by glare.
- Lane marking not visible due to rain, snow, fog.

The system detects system degradation and alerts the driver (***)

- Sensors covered, obstructed or damaged.
- GPS unavailable
- System failures

Precise position determination

The driving automation uses GPS is used with real-time corrections using LIDAR measurements on pre-mapped highways to determine the vehicle's location.

Attention system

The Driver Attention System (this is not the Mediator driver monitoring system but the baseline system in the vehicle) with head pose and eye gaze software helps make sure your eyes are on the road, and it alerts you when you need to pay more attention.

If the driver does not respond to alerts, the vehicle will slow in your lane of travel and eventually brake to a stop.

Lane centring

The driving automation uses GPS with real-time corrections using LIDAR measurements on pre-mapped roads, and the Lane (markings) Sensing Camera to determine the vehicle's location and position in the lane.

This combination provides higher availability which allows a longer take-over time and thus hands-free driving.

Adaptive Cruise Control for braking and acceleration

The system works with the vehicle's Adaptive Cruise Control system, which is designed to detect vehicles in your path, accelerate or brake your vehicle based on traffic conditions around you, and keep a driver-selected following gap time from a vehicle ahead, even in stop-and-go traffic.

Lane change

Automatic Lane Change functionality allows the vehicle to change lanes without any input from the driver while the driving automation is active. When Automatic Lane Change is engaged, the gauge cluster will inform the driver when a lane change will occur and will gently guide the vehicle into a desired lane around the vehicle in its path. When the driving automation is active, the vehicle will also change lanes if the current lane is ending, as well as pass (to the left) around slower moving vehicles and return to its original lane.

For Lane Change on Demand, when the driver activates the turn signal, the system will look for an acceptable opening in the indicated lane and alert other vehicles that a lane change is imminent. If the indicated lane is determined to be open, the vehicle will merge into the desired lane. Or, if the desired lane is unavailable, it will notify the driver that merging must be manually completed. The system will display messages, such as "looking for an opening" or "changing lanes," to keep the driver informed.

Safety benefits of Mediator in case of driver fatigue

If driver fatigue is detected by the Mediator driver monitoring system => Mediator cannot advise to turn on the adaptive cruise control and lane centring system as Mediator cannot determine that the vehicle is within the ODD.

Mediator can provide a warning of driver fatigue to the driver though.

False alarms of the Mediator driver monitoring system may result in the driver turning off the Mediator driver monitoring system and thus negating the safety benefit.

Safety benefits of Mediator in case of severe distraction or incapacitation

If severe distraction or driver incapacitation is detected by the Mediator driver monitoring system => Mediator cannot instruct to turn on the adaptive cruise control and lane centring system as Mediator cannot determine that the vehicle is within the ODD.

Mediator can provide a warning though. If there is a passenger on board he/she can try to take over the steering and possibly (although this requires more time) remove the foot of the driver from the gas pedal. Or the driver may just in time resume the steering and braking and acceleration tasks in case of severe distraction.

False alarms of the Mediator driver monitoring system may result in the driver turning off the Mediator driver monitoring system and thus negating the safety benefit.

SAE level 3 of driver automation

Which tasks does the level 3 driving automation perform

These automated driving features can drive the vehicle under limited conditions

Purpose of level 3 driving automation

Improve safety by reducing workload (and preventing fatigue).

Driver responsibilities

The driver must take over the driving tasks when

- The driving automation detects that the circumstances will get outside the ODD and alerts the driver (see ** below)
- When the driving automation detects system degradation and alerts the driver

If the driver does not react the vehicle is brought to a safe standstill.

Operational Design Domain

E.g., on the highway in a traffic jam up to a certain speed

The driving automation detects the following circumstances and alerts the driver (because they are outside the ODD (**)

The automated driving feature will not operate unless all required conditions are met.

The system detects system degradation and alerts the driver (***)

In case of:

- Sensors covered, obstructed or damaged.
- GPS unavailable
- System failures

Safety benefits of Mediator in case of driver fatigue

If fatigue is detected by the Mediator driver monitoring system => if the traffic jam chauffeur was turned off and the vehicle is within the ODD, the driver is advised by Mediator to turn on the traffic jam chauffeur.

The driver can turn on the traffic jam chauffeur.

There is a safety benefit (fewer crashes in traffic jams caused by fatigue) if:

- The Mediator driver monitoring system is available (no technical failures).
- The Mediator driver monitoring system is turned on by the driver (driver thrusts the system and accepts it)
- The traffic jam chauffeur was not turned on and is available.
- The vehicle is within the ODD

False alarms of the Mediator driver monitoring system may result in the driver turning off the Mediator driver monitoring system and thus negating the safety benefit.

Safety benefits of Mediator in case of severe distraction or incapacitation

If severe distraction or driver incapacitation is detected by the Mediator driver monitoring system => Mediator instructs the traffic jam chauffeur to take over if within the ODD. The traffic jam chauffeur brings the vehicle to a safe standstill if the driver does not respond to the vehicle within 10 seconds.

There is a safety benefit (fewer crashes caused by severe distraction or incapacitation) if:

- The Mediator driver monitoring system is available (no technical failures).
- The Mediator driver monitoring system is turned on by the driver (driver thrusts the system and accepts it)
- The traffic jam chauffeur was not turned on and is available.
- The vehicle is within the ODD

False alarms of the Mediator driver monitoring system may result in the driver turning of the Mediator driver monitoring system and thus negating the safety benefit.

SAE level 4 of driver automation

Which tasks does the level 4 driving automation perform

These automated driving features can drive the vehicle in a restricted area (e.g., driverless taxi / public transportation / transportation for disabled people, in a city)

Purpose of level 4 driving automation

Economics:

- Cheaper (e.g., driverless taxi)
- Efficiency (e.g., vehicle drives autonomously to next user in case of vehicle sharing)
- Provision of transportation (e.g., driverless transportation for disabled people, driverless public transportation)
- Etc

Driver responsibilities

None

Operational Design Domain

In a restricted area (e.g., a city).

In limited weather conditions.

The driving automation keeps the vehicle in the restricted area and stops the vehicle at a safe location when weather conditions deteriorate.

The driving automation stops the vehicle at a safe location in case of system degradation.

The driver automation will not operate unless all required conditions are met.

Safety benefits of Mediator in case of driver fatigue

If fatigue is detected by the Mediator driver monitoring system => if the autonomous driving automation was turned off and the vehicle is within the ODD, the driver is advised by Mediator to turn on the autonomous driving automation.

The driver can turn on the autonomous driving automation.

There is a safety benefit (fewer crashes caused by fatigue) if:

- The Mediator driver monitoring system is available (no technical failures).
- The Mediator driver monitoring system is turned on by the driver (driver thrusts the system and accepts it)
- The autonomous driving automation was not turned on and is available.
- The vehicle is within the ODD
- The vehicle is equipped with controls and that there is a driver behind the controls.

The safety benefit is greater than for SAE level 3 because the automation can take over in a larger area (e.g., a city instead of a traffic jam on a highway).

False alarms of the Mediator driver monitoring system may result in the driver turning off the Mediator driver monitoring system and thus negating the safety benefit.

Safety benefits of Mediator in case of severe distraction or incapacitation

If severe distraction or driver incapacitation is detected by the driver monitoring system => Mediator instructs the autonomous driving automation to take over if within the ODD

There is a safety benefit (no crashes due to severe distraction or incapacitation) if:

- The Mediator driver monitoring system is available (no technical failures).
- The Mediator driver monitoring system is turned on by the driver (driver thrusts the system and accepts it)
- The autonomous driving automation was nor turned on and is available.
- The vehicle is within the ODD.
- The vehicle is equipped with controls and that there is a driver behind the controls.

The safety benefit is greater than for SAE level 3 because the automation can take over in a larger area (e.g., a city instead of a highway).

False alarms of the Mediator driver monitoring system may result in the driver turning of the Mediator driver monitoring system and thus negating the safety benefit.

SAE level 5 of driver automation

Which tasks does the level 5 driving automation perform

These automated driving features can drive the vehicle in all conditions

Purpose of the level 5 driving automation

Economics:

- Cheaper (e.g., driverless taxi)
- Efficiency (e.g., vehicle drives autonomously to next user in case of vehicle sharing)
- Provision of transportation (e.g., driverless transportation for disabled people, driverless public transportation)
- Etc

Driver responsibilities

None.

Operational Design Domain

No limitations.

The driving automation stops the vehicle at a safe location in case of system degradation.

The driver automation will not operate unless all required conditions are met.

Safety benefits of Mediator in case of driver fatigue

If fatigue is detected by the Mediator driver monitoring system => if the autonomous driving automation was turned off, the driver is advised by Mediator to turn on the autonomous driving automation.

The driver can turn on the autonomous driving automation.

There is a safety benefit (fewer crashes caused by fatigue) if:

- The Mediator driver monitoring system is available (no technical failures).
- The Mediator driver monitoring system is turned on by the driver (driver thrusts the system and accepts it)
- The autonomous driving automation was not turned on and is available.
- The vehicle is equipped with controls and that there is a driver behind the controls.

The safety benefit is greater than for SAE level 4 because the automation can take over everywhere instead of only in a restricted area.

False alarms of the Mediator driver monitoring system may result in the driver turning off the Mediator driver monitoring system and thus negating the safety benefit.

Safety benefits of Mediator in case of severe distraction or incapacitation

If severe distraction or driver incapacitation is detected by the Mediator driver monitoring system => Mediator instructs the autonomous driving automation to take over

There is a safety benefit (no crashes due to severe distraction or incapacitation) if:

- The Mediator driver monitoring system is available (no technical failures).
- The Mediator driver monitoring system is turned on by the driver (driver thrusts the system and accepts it)
- The autonomous driving automation was not turned on and is available.
- The vehicle is equipped with controls and that there is a driver behind the controls.

The safety benefit is greater than for SAE level 4 because the automation can take over everywhere instead of only in a restricted area.

False alarms of the Mediator driver monitoring system may result in the driver turning of the Mediator driver monitoring system and thus negating the safety benefit.

D.2 Results and discussion

Using Mediator for advising the driver turn on the driving automation in case of fatigue.

For SAE level 0,1,2 there is an expected safety benefit (fewer crashes due to fatigue) of using Mediator for warning the driver that he /she is fatigued:

- The Mediator driver monitoring system is available (no technical failures).
- The Mediator driver monitoring system is turned on by the driver (driver trusts the system and accepts it)

Starting from SAE level 3, there is an expected safety benefit (fewer crashes due to fatigue) of using Mediator for advising the driver turn on the driving automation in case of fatigue if:

- The Mediator driver monitoring system is available (no technical failures).
- The Mediator driver monitoring system is turned on by the driver (driver trusts the system and accepts it)
- The driving automation was not turned on and is available.
- The vehicle is within the ODD (higher levels of driving automation have a larger ODD).

Higher levels of driving automation have a larger ODD and consequently the safety benefit becomes larger.

It is judged to be very worthwhile to assess this potential application of a Mediator-like system in further detail. However much of the safety benefit depends on that the situation where driving automation initially was turned off while the driver was fatigued, the likelihood of which may not be very high.

Using Mediator for turning on the driving automation in case of severe distraction or incapacitation

Starting from SAE level 3 of driving automation, there is an expected safety benefit (fewer crashes due to severe distraction and incapacitation) of using Mediator for turning on the driving automation in case of severe distraction or incapacitation if:

- The Mediator driver monitoring system is available (no technical failures).
- The Mediator driver monitoring system is turned on by the driver (driver thrusts the system and accepts it)
- The driving automation was not turned on and is available.
- The vehicle is within the ODD (higher levels of driving automation have a larger ODD).

Higher levels of driving automation have a larger ODD and consequently the safety benefit becomes larger.

It is judged to be very worthwhile to assess this potential application of a Mediator-like system in further detail.