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Safety and impact assessment for seamless interactions through human-machine interfaces: indicators and practical considerations

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Abstract

Autonomous Vehicles are expected to change the existing transportation systems radically and at the intermediate SAE automation levels before highly automated vehicles (i.e., SAE levels 2 and 3), the driving task will still require human interactions with the vehicle. To that end, Human-Machine Interfaces (HMIs) are expected to play a key role in the cooperation between users and vehicles. The current study proposes a methodology for assessing new types of HMIs for automated vehicles. The study aims to cover this gap by proposing a method for assessing novel types of HMIs for automated vehicles. Also, directives related to indicators for assessing safety and impact, and practical considerations are given. The outcomes can contribute to guiding further research in this direction and additionally can be transferred and expanded to other automated technologies and systems.

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Keywords: Automated Driving; Autonomous Vehicles; Safety & Impact Assessment; Human-Machine Interfaces (HMI); Key Performance Indicators (KPIs); Academia-Industry Collaboration

1. Introduction

Autonomous Vehicles (AVs) are expected to change the existing transportation systems radically (Elvik, 2021;

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Fagnant and Kockelman, 2015). A high market penetration rate of AVs is estimated to enhance road capacity and fuel efficiency, as well as decrease environmental emissions (Elvik, 2021; Fagnant and Kockelman, 2015; Mersky and Samaras, 2016; Ye and Yamamoto, 2018). At SAE automation levels up to level 3 (i.e., SAE level 0-3; up to conditional automation), the driving task will still require human interventions and interactions with the vehicle (SAE, 2016). Hence, Human-Machine Interfaces (HMIs) are expected to play a key role in the cooperation between passengers and vehicles (Forster et al., 2016) at these intermediate SAE automation levels. Two main requirements, have to be fulfilled for successful usage of HMIs. These are a) HMIs should make drivers understand their everyday actions regarding environmental monitoring and active intervention (Carsten and Martens, 2019), and b) the HMI should also be designed to understand the required interaction and if it is in accordance with the driver's state. This is particularly important on takeover requests (TORs); during a transition from automated to manual driving, where the HMI-AV should ensure that the driver’s state is sufficient to take back control and drive manually. Furthermore, HMIs should be designed to handle unexpected situations when the drivers are required to gain control of the vehicle, especially during critical situations. Additionally, HMIs should be designed to deal with the changing role of the driver as levels of automation increase (Hancock et al., 2009). Inappropriate handling and incorrect recognition negatively affect the safety level. At the same time, from the drivers’ perspective, the drivers need to develop an adequate level of trust, skills, and situation awareness in the system to feel safe while driving (Richardson et al., 2018). Nevertheless, these interfaces have not yet been proven to lead to safer and smoother trips and which degree.

Therefore, a detailed human-centered investigation, by a study, of the interaction between the user and the driver should be conducted. Within the proposed methodology special focus is also given to the execution of non-driving related tasks (NDRTs) during driving, e.g., working on an electronic device, eating, drinking, reading, watching entertainment content, and texting or calling on their phones (Kim et al., 2018) and becomes even more important during the TORs.

The main goal of this study is to propose a methodology for assessing new types of HMIs for automated vehicles and consequently cover this literature gap. The study was conducted within the EU H2020 HADRIAN (**H**olistic **A**pproach for **D**river **R**ole **I**ntegration and **A**utomation Allocation for European Mobility **N**eeds) project. HADRIAN aims at developing an innovative HMI (titled fluid-HMI or f-HMI) that will provide seamless (“fluid”) interactions between the driver and the automated vehicle. The driver role for automated vehicles is also investigated and defined using a holistic user-centered approach that addresses shortcomings of current development and design processes to achieve high impact and wide-reaching acceptance of automated vehicles. Another motivation for conducting this study is to fill the gap in the existing literature concerning the development of safety and impact assessment of HMIs on Automated Driving (AD) applications. This paper attempts to give directives related to indicators for assessing safety and impact, and practical considerations for assessing the development of fluid interactions between the user and the HMI through AD. Moreover, the outcomes can contribute to guiding further research in this direction and additionally can be transferred and expanded to other automated technologies and systems.

2. Methodology

2.1. Project Overview

The methodology which is applied during the HADRIAN project is given below. To understand the individual steps, a short overview of the HADRIAN project and its framework along with the investigated parameters i.e., levels of automation, innovations, and use cases is introduced. Based on the knowledge of innovations, the methodology of identifying critical key performance indicators (KPIs) and the global results of this process are discussed. Those lead to sequentially presented dedicated KPIs list, relevant to the assessment taking place in the study. To be able to put such KPI assessments into a context a baseline for the measurement is given. In the subsequent phase, the assessment method follows along with the identified critical KPIs, aiming at quantifying the assessment. In this section, the requirements for each indicator are given as well. Then, the comparison context of the HADRIAN is explained by describing the “baseline” HMI. After that, practical considerations are given about the developed safety and impact assessment. Parts of Sections 2.1-2.2 are provided comprehensively since are not the study core but are necessary to give a brief overview of the background of the assessment methodology which is the key topic of the present study.

The HADRIAN system focuses on seven advances and innovations, as listed in Table 1, that encompass five HADRIAN-defined levels of automated driving and transitions between them, as indicated in Table 2. The major goal of the assessment is to demonstrate the improvements of the f-HMI innovations regarding safety and impact. As shown in Table 1, the innovations are assigned to four different categories (i.e., predictability, fluidity monitoring, and tutoring) that HADRIAN aims to improve with its innovations.

Table 1. The 7 HADRIAN Innovations.

Innovation Number	Symbol	Innovation Description	Predictability	Fluidity	Monitoring	Tutoring
1		Awareness assistant to simplify the manual driving task for elderly drivers		X		
2		Reduce the need for the driver to monitor the environment and automation during ADL 2	X	X		
3		Provide minimum guaranteed time for human driver to transition from automated driving to manual driving	X	X		
4		Guarantee minimum duration of automated driving at level 3 / 3+	X	X		
5		Active driver monitoring & fluid interventions	X	X	X	
6		Adaptive tutoring to improve driver / user skills, knowledge, and competences to use the automated driving system		X		X
7		Guardian Angel as safety protector during manual driving		X		

Based on the aforementioned innovations three specific use cases (or mobility scenarios) are studied within the project. The use cases are a) an elderly driver, b) a truck driver, and c) an office worker driver. Each of these has distinct mobility requirements and necessitates unique driving circumstances. Out of their requirements and the innovations, the 5 levels of HADRIAN automation are developed, as presented in table 2. These include the environment awareness assistant (EAA) and the guardian angel (GA) as supportive levels to the HADRIAN ADL2, 3 and 3+ which offer automated driving with guaranteed transition times from 5 to 60 seconds.

Table 2. The 5 Levels of HADRIAN Automation.

Automation Name	Description
Environment Awareness Assistant (EAA)	The EAA supports the driver during manual driving mode, proving critical driving-related information to the driver when needed (e.g., a road sign not recognized by the driver). This system is addressed to elderly drivers since it aims to simplify the driving tasks and enabling them to drive safely even under challenging situations.
HADRIAN ADL2	HADRIAN ADL2 differs by a standard SAE L2 by reducing human monitoring need during ADL2 and by providing a guaranteed transition time to manual driving (e.g., 5 seconds). Moreover, it is supported by an active driver monitoring and fluid intervention system, meaning that the system intervenes only when it detects that the driver does not sufficiently check the environment.
HADRIAN ADL3	HADRIAN ADL3 is an improved version of standard SAE L3 by introducing an even longer guaranteed transition time to manual driving (for instance, 15 seconds) and by defining the starting and ending points of the ADL3 areas using road infrastructure support. Moreover, it supports an active driver monitoring and guidance during automated driving and transition back to manual driving. The active driver monitoring enables the driver to be sufficiently engaged and to perform only the defined allowed activities. The guidance system helps the driver to check all the relevant parameters while taking over.
HADRIAN ADL3+	ADL3+ is based on HADRIAN ADL3, but it offers again a longer guaranteed transition time to manual driving (for instance, 60 seconds) and a guaranteed minimum ADL3 duration (at least 30 minutes).
Guardian Angel (GA)	The GA actively supports the driver during manual driving mode, monitoring the manual driving performance and correcting it when an unsafe condition arises (e.g. correction of the steering angle). This system is targeted to elderly drivers that might have lost some of their driving skills.

2.2. Assessment Development

For the assessment of fluid-HMI advancements, a set of KPIs was developed and is provided within this paper. These KPIs serve as input for a total score reflecting the improvement of safety level as well as the overall impact of the produced HMI and the project innovation concerning the defined baseline.

A crucial aspect of the HMI safety impact assessment is the identification of suitable KPIs. The process of KPI identification started from a holistic literature review of risk factors for automated driving in the three different use cases of automated mobility, focusing on elderly drivers, office-worker commuters, and professional truck drivers. Furthermore, previous research projects and studies that executed an impact and safety assessment in terms of AD were reviewed to conclude that first, the use of KPIs was the most suitable method of assessment, and second identify the most relevant, previously exploited KPIs. The methodology of the aforementioned review along with the findings is already well discussed in D5.1 (Katrakazas et al., 2020).

Within the project, driving scenarios were developed for each use case based on the HADRIAN scope and use case subjects' needs and were titled “driving tasks”. The driving scenarios are published in detail in D1.1. (Mörtl et al., 2020) and provide detailed information about the road, the environment, and other road users. Subsequently, for each driving task, description and subtasks were created. The driving tasks consist of all the necessary descriptions and elements of the driving scenarios in which the HADRIAN project aims to test the developing innovations. Considering all the innovations, levels of automation, and use cases, the driving tasks were created and distinguished into subtasks with their description. The subtasks include a detailed description of driver-required actions, traffic requirements, human-machine required interactions, and automation constraints during each developed driving scenario. An analysis of the driving subtasks revealed the risk factors which were potentially present in the driving “system” during the hypothetical driving scenarios. For all of the subtasks, it was critical to describe the different needs and hazards, such as the driver's and environmental sensing needs, user-centered interface needs, and safety risks. This analysis was titled “hazard identification procedure” and establishes the relation of the potential risk factors during the predefined driving scenarios with the key performance indicators and closes the loop of a reflected KPI development. The goal of hazard identification was to ensure that the calculated KPIs were accurate. The KPIs were then linked to see if they might be utilized to assess the related hazard or necessity. Some of the KPIs gathered from the literature were insufficient to evaluate these hazards identified, and thus more KPIs were created and adapted to the HADRIAN requirements.

For many years, the “system” concept centered only on the autonomous vehicle's interdependence and collaboration with the HMI. A unique system concept in the HADRIAN project was included in the aforementioned hazard identification process including dependence of vehicle, driver, HMI, infrastructure, and traffic, to identify crucial multiparametric KPIs on hazard components. The term "system" was adopted as the basis for hazard identification. The “system” shed light on which components the potential hazards were detected and after the identification, a brokedown was conducted at the subtasks level. For each driving subtask, potential hazards were discovered utilizing the "new system concept" during the hazard identification phase.

In a subsequent step of the project, the KPIs were refined with a focus on practical application, and measurement guidelines were given to ensure robust safety and impact assessment, as in D5.2 & 5.3 (Jany-Luig et al., 2021; Prueggler and Jany-luig, 2022). This approach has been developed in collaboration between academic and industrial stakeholders to safeguard a common ground for future assessment of automated vehicle projects. The derived KPIs were further refined in parallel with the development of the driving simulator scenarios of the project, as described in D5.2 (Jany-Luig et al., 2021). More information related to the entire method can be found in (Sekadakis et al., 2021), as well as the Deliverables of WP5 of the EU HADRIAN project (i.e., D5.1-D5.3) along with forthcoming publications and deliverables as the project proceeds and will be published under the following link of the project (https://hadrianproject.eu/results/).

The KPIs were separated into two main groups which are safety with objective measurements in the upper part of Figure 1 and impact with subjective measurements in the lower part of Figure 1. The safety group contains indicators such as Maneuver Quality, Transition Time, Reaction Time, Distraction, Conflicts, Automation Engagement, Time-to-collision, Take-overs number, and Driving measurements. Those indicators are quantifiable by measurement systems and thresholds can be set for certain levels of quality. Similarly, the indicators in the general impact group were Acceptability, Workload, Comfort, Usability, Comprehensibility, Intend to Use, Trust, Control Feeling, and Safety Feeling. The assessment of such safety and subjective indicators can only be established by including the testing subject through questionnaires, conversations, or workarounds with complex published calculations out of human measurements.

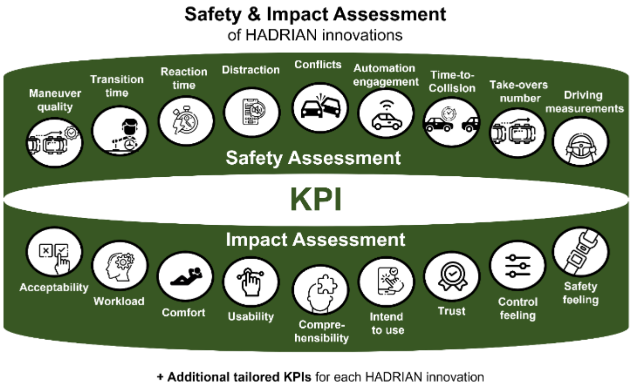

Fig. 1. KPIs of the safety and impact assessment.

A final list of 18 KPIs was extracted out of the most relevant, previously exploited KPIs and their application and usability for the selected use cases, as shown in Table 3. The KPI overview shows the measurement approach as well as the requirements for each KPI. Some of the measurement approaches have real-time capability, and some of the values are generated in a postprocessing procedure.

To that point, a comprehensive overview of the assessment aim is provided, within the HADRIAN project, an assessment will be implemented for all the aforementioned studies to capture and analyze the enhancement achieved by the HADRIAN innovations. The enhancement of the HADRIAN system will be obtained through comparison with corresponding state-of-the-art AD systems or HMIs, which will act as "baseline" systems. For this purpose, an "HADRIAN-tailored" safety and impact assessment methodology was developed using special KPIs. The estimation of these KPIs is obtained through driving metrics and subjective measurements with questionnaires during the HADRIAN studies using driving simulators. This KPI-based assessment consists of 9 KPIs related to safety and driving performance and 9 KPIs related to the impact on the drivers' perspectives. At the final stage of the assessment, a total score will be calculated taking into account the developed KPIs to obtain one total score for "baseline" and one for HADRIAN innovations, which will be exploited for overall comparison. In the following figure, the KPIs of the assessment are presented. The expected outcome of the assessment is to capture all the driving aspects that are going to be improved after the implementation of the HADRIAN innovations.

Table 3. KPIs and their measurement approach.

ID	KPI	Description	Measurement Approach
		Safety - Objectives Measurements	
1.1	Maneuver Quality	Manoeuvre evaluation: Quality of the manoeuvre	Steering wheel torque conflict (i.e., the number of agreements [or disagreements] between human and machine intentions) Percentage of agreements over the trip duration (i.e., agreements/ maneuvers over trip duration)
1.2	Transition Time	Time of transition between automated and manual driving (from the first transition signal to safe control)	Measured in (s) between the moment that the vehicle requests the driver to take over and driver checks all the necessary information
1.3	Reaction Time	Time of reaction between automated and manual driving (from the first transition (software knowledge) to first driver´s interaction with vehicle)	Measured in (s) between the moment that the vehicle requests the driver to take over and the moment the driver actually takes over (interaction with vehicle (steer wheel/braking pedal))
1.4	Distraction	Driver's Distraction (High Level): Time that the driver is not looking outside the window	Measure the "gaze on the road" as submodel state of the fit2drive model (%: Gaze on the road (s) / Total trip duration (s))

1.5	Conflicts	Number of conflicts: Total number of conflicts with other road users (including VRUs) and infrastructure	One out of: • Time-to-Collision (TTC) < 1.5sec (preferred) • Headway time < 0.7sec • Deceleration Rate to Avoid the Crash (DRAC) > 3.4 m/sec^2 Plus the time stamp and GPS position of the conflict Plus collision or no collision occurred (0 or 1)
1.6	Automation Engagement	Percentage of time in ADL2/3 (or the study focus) is engaged	Time AD engaged / Total trip duration Separately for ADL 2 and 3
1.7	Time-to-collision	Frequency of TTC < 3s over the whole scenario.	Measured as: number of occasions where TTC was less than 3 seconds /10km (per 10km)
1.8	Take-overs number	Number of Takeovers	The number of takeovers (AD to manual) in total and per km. Categorize the expected and unexpected takeovers (i.e, unexpected takeovers: triggered by the operator) Also, the number of transitions in total (both AD to manual and manual to AD)
1.9	Driving measurements	Driving measurements: Speed, Headway Time, Headway Distance, TTC, Lateral Distance, Lateral Deviation (from the center of the lane), Longitudinal Acceleration/Deceleration, Lateral Acceleration/Deceleration.	Driving Data (aggregated per minute) (in m, km/h, s, m/s2)
		Impact - Subjective Measurements	
2.1	Acceptability	Acceptability ratings	Do you think the system provides an acceptable driving experience? 9-point Likert scale, strongly disagree–strongly agree
2.2	Workload	Subjective Workload	NASA-TLX questionnaire, 6 dedicated questions
2.3	Comfort	Comfort	How much comfortable did you feel using the system? 9-point Likert scale, low–high
2.4	Usability	Usability	How do you rate the usability of the system? 9-point Likert scale, low–high
2.5	Comprehensibility	Comprehensibility	Did you clearly understand all the messages and interactions from the system? 9-point Likert scale, strongly disagree–strongly agree
2.6	Intend to Use	Intend to Use	How often do you intend to use the system if it is feasible in the future? 9-point Likert scale, never–always
2.7	Trust	Trust	How much do you trust the system? 9-point Likert scale, low–high
2.8	Control Feeling	Control Feeling	How do you rate the feeling of being able to control the vehicle during the experiment? 9-point Likert scale, failure–perfect
2.9	Safety Feeling	Safety Feeling	How safe did you feel during the experiment? 9-point Likert scale, very dangerous – very safe

2.3. "Baseline" Definition

As previously stated, the HADRIAN innovations will be compared to a "baseline condition" to determine the safety and impact enhancement. The definition of the term "baseline" is crucial for the assessment as it gives insights into the comparison context. As a result, to define the "baseline", a consensus on a single baseline definition was reached through harmonizing various HMI innovations. A common baseline was established for all HADRIAN trials to ensure consistency in assessment.

The harmonized baseline definition is the following: " *The baseline is an initial set of conditions/ states i.e., driving without any innovative driving system (state-of-the-art driving system) and it is used for comparison (or a control) with the examined innovative driving system. More specifically, within the HADRIAN project, the baseline will be a state-of-the-art (or nowadays') driving system and this system will be compared to the HADRIAN innovative system; with a total aim to evaluate the safety and impact enhancement of HADRIAN innovations"* (Prueggler and Jany-luig, 2022).

All simulator studies feature driving situations (or even parts of routes) with state-of-the-art driving systems (without fluid HMI innovations), followed by driving scenarios with innovative HADRIAN driving systems (with fluid HMI innovations). Figure 2 shows a graphical representation of the comparison context inside the safety and impact assessment of HADRIAN system advancements.

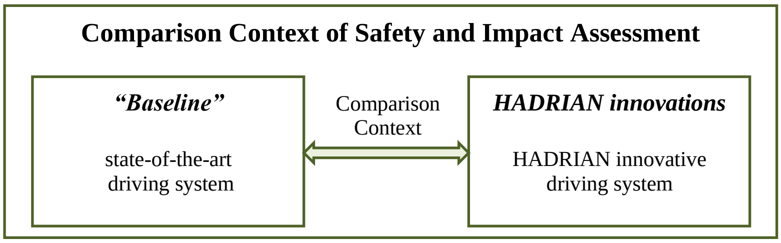

Fig. 2. Comparison context within the safety and impact assessment (Prueggler and Jany-luig, 2022).

3. Practical Applications and considerations for collaboration between industry and academia

The safety assessment methodology described in the previous sections can act as a guideline for a practical assessment of innovative systems to be embedded in automated vehicles. The holistic nature of the methodology can assist in identifying all the necessary indicators needed for assessing a variety of systems, regardless of the sensory capabilities. For example, essential KPIs can be defined for the haptic, camera, or radar-based systems as well as a combination of those. The only aspect that needs refining from researchers and the industry is the aggregation level of the measurements needed to define the KPIs. This can be further tailored according to the application of the methodology. For example, if real-time assessment is needed per-second aggregation or 30-second intervals might be enough to judge the safety of a system. On the other hand, acceptance and comfort might be treated at a post-trip basis. In that way, researchers and practitioners could tailor their safety assessment KPIs accordingly and use a well-identified baseline for comparing the performance of newly developed automated systems.

The contribution to future HMI developments of the established methodology is that it is already harmonized between research facilities and the vehicle industry using the inputs of collaboration between transportation and automotive engineers as well as the vehicle industry. As a result, the research-oriented knowledge is transferred into industry-oriented considerations and applications, which allows realistic assessment results. The KPI list, the baseline definitions as well as the corresponding measurements are thus validated both from state-of-the-art research methodologies as well as the functional guidelines from the automotive industry. Nevertheless, openness in terms of data and techniques, as well as cost-benefit evaluations of the measurements and components needed for them, is an essential part of the collaboration between industrial and academic partners.

As vehicle automation is at the epicenter of current transportation research, the active collaboration between researchers and industrial partners is essential for achieving realistic and evidence-based results, that will lead to actual road safety enhancement for all road users and stakeholders.

4. Conclusions

Autonomous Vehicles (AVs) are expected to change the existing transportation systems radically. Since at the intermediate SAE automation levels (i.e., SAE levels 2, 3; partial and conditional automation), the driver is still in the loop, the driving task will still require human interventions and interactions with the vehicle. Hence Human-Machine Interfaces (HMIs) are expected to play a key role in the cooperation between users and vehicles. The current study presents a methodology for assessing new types of HMIs for automated vehicles along with measurement guidelines and requirements. Directives related to indicators for assessing safety and impact, and practical considerations of the assessment development of fluid interactions between the user and the HMI through AD are given. Future work on HMIs for automated driving can build on the developed assessment method as its foundation is built on both major development parties, the industry, and academia.

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