Key Performance Indicators for safe fluid interactions within automated vehicles

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Abstract

This study attempts to identify critical Key Performance Indicators (KPIs) to assess the safety and general impact of fluid interactions between the user and Human Machine Interfaces (HMIs) within automated vehicles. More specifically, safety, driving performance, and general impact indicators were considered for such an assessment. The identification of KPIs was based on a literature review, previous knowledge obtained from similar research programs and a hazard identification process. The derived KPIs were categorized into two main categories, namely safety and general impact, and these categories were distinguished in 11 additional subcategories. The most critical KPIs within the safety group were found to be take-over time as well as the number of take-overs, whereas comfort, the feeling of safety and trust were the most crucial impact-related KPIs. Nevertheless, validation of those KPIs in field trials is, however, deemed necessary.

Keywords: *Automated Vehicles, Human Machine Interface - HMI, Safety and Impact Assessment, Key Performance Indicators - KPIs*

Περίληψη

Αυτή η εργασία επιχειρεί να εντοπίσει Βασικούς Δείκτες Απόδοσης (KPIs) ώστε να αξιολογήσει την ασφάλεια και τη γενική επίπτωση των αδιάλειπτων αλληλεπιδράσεων, μεταξύ του επιβάτη και μίας Διεπαφής Ανθρώπου-Μηχανήματος (HMI) στα πλαίσια ενός αυτόνομου οχήματος. Πιο συγκεκριμένα, δείκτες ασφάλειας, οδικής επίδοσης και γενικών επιπτώσεων συμπεριλήφθηκαν για την αξιολόγηση. Προκειμένου να εντοπιστούν οι δείκτες KPIs, πραγματοποιήθηκε βιβλιογραφική ανασκόπηση, διερευνήθηκε η υφιστάμενη γνώση από παρόμοια ερευνητικά προγράμματα και εκτελέστηκε μια διαδικασία αναγνώρισης κινδύνου. Έπειτα, οι δείκτες κατηγοριοποιήθηκαν σε δύο κύριες κατηγορίες, αυτούς που αφορούν την ασφάλεια και εκείνους που αφορούν την γενική επίπτωση. Οι πιο κρίσιμοι δείκτες εντός της κατηγορίας που αφορά την ασφάλεια είναι ο απαιτούμενος χρόνος μεταξύ αυτόνομης και μη αυτόνομης οδήγησης καθώς και η συχνότητα των φορών που απαιτήθηκε, ενώ στην ομάδα των γενικών επιπτώσεων, η άνεση, η αίσθηση ασφάλειας και η εμπιστοσύνη. Ωστόσο, κρίνεται απαραίτητη η επαλήθευση αυτών των Βασικών Δεικτών Απόδοσης (KPIs) σε δοκιμές πεδίου.

Λέξεις Κλειδιά: *Αυτόνομα οχήματα, Διεπαφή Ανθρώπου-Μηχανήματος, Αξιολόγηση Ασφάλειας και Επιπτώσεων, Βασικοί Δείκτες Απόδοσης*

1. Introduction

Connected and Automated Vehicles (CAVs) are expected to dominate the market share in 2050, if the CAV prices decrease at an annual rate of 15% or 20% (Talebian & Mishra, 2018). As road fatalities claim approximately 1.35 million deaths per year (WHO, 2020), assessing the levels of safety during conventional and automated driving (AD) becomes essential for mitigating road fatalities and injuries. Towards that end, the automobile industry aims to reach the absolute goal of SAE level 5, fully automated vehicle (AV), which requires no human input (SAE, 2016). It is important, however, to assure high levels of trust amongst users in order to achieve higher acceptance and consequently higher penetration rates in the market share (Manchon et al., 2020).

With regards to the positive impact of CAVs on passengers and drivers, a significant proportion of the population, such as the elderly, children, and disabled will have the opportunity to commute in contrast to conventional vehicles. Additionally, the passengers or even the driver will be able to execute 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).

At the intermediate SAE automation levels prior to the highly automated (i.e., SAE levels 2, 3), the driving task will still require human inputs and interventions. Human Machine Interfaces (HMIs) are expected to play a key role between user-vehicle interaction. To that aim, Human Machine Interfaces (HMIs) could support the calibration of trust, which is an essential requirement for safe and comfortable operation (Carsten & Martens, 2019) of CAVs. The role of HMI is to make humans understand what is expected of them in terms of environment monitoring and active intervention (Carsten & Martens, 2019). Nevertheless, the HMI should also be designed in order to understand the required interaction and if it is in line with the driver's state. Otherwise, the safety level will be negatively affected by driving requirements that the driver could not handle appropriately due to the incorrect recognition of the driver's state.

It is essential to develop a “safer” automated vehicle with a seamless HMI, which will assist in reducing and delimiting human errors during driving. In this context, by developing a comprehensive assessment, opportunities are created to evaluate the effect of new HMIs on safety as well as their general impact. This paper attempts to identify critical KPIs that are capable of assessing the safety and general impact of fluid interactions between the user and the HMI within automated vehicle applications. The exported KPIs can contribute to guide further research in this direction, and additionally can be exploited and expanded to other automated technologies and systems.

The work included in this study was conducted within the EU H2020 HADRIAN project, which aims at developing an innovative HMI (titled as fluid-HMI or f-HMI) that will provide seamless (“fluid”) interactions between the driver and the automated vehicle. The project is based on three use cases (or mobility scenarios), which are illustrated in **Figure 1**. The three use cases consist of an elderly driver, a truck driver, and an office worker driver, each of which has different mobility needs and requires special conditions in terms of driving performance.

(a) (b) (c)

Figure 1: *The HADRIAN use cases: (a) Elderly (b) Truck (c) Office Working Driver*

The paper is structured as follows; after the introduction, the methodology follows, including three main subsections. The first presents the initial step of the methodological framework of the safety and impact assessment framework of HADRIAN, part of which is the identification of KPIs. The second describes the KPIs derived from the literature review and they were included in the development of the KPIs list. The third presents a brief example of the aforementioned methodological approach. After that, results are presented in terms of findings which structures the final list of the KPIs. Results are followed by the study limitations and then, conclusions for relevant stakeholders are drawn.

2. Methodology

Firstly, the methodological approach is presented briefly with the aim to understand the structure of the study, as the study is structured according to the flow of the methodological approach. **Figure 2** represents the methodological approach of the safety assessment within HADRIAN. Specifically, the HADRIAN framework sets the parameters (i.e., levels of automation and innovations) and use cases by framing the desired driving scenarios or tasks. Each driving tasks consist of description and subtasks. The driving tasks consist of all the necessary descriptions and elements in the driving scenarios in which the HADRIAN project aims to test its innovations. An analysis named hazard identification, considering the driving subtasks description, revealed the risk factors which were potentially present during the driving scenarios. In the subsequent phase, relevant KPIs were identified with the purpose of quantifying the potential risk factors within the driving scenarios and considering existing knowledge from literature (i.e., literature review KPIs). To this point, the list of KPIs was concretized and it was designed to be applied within the HADRIAN project by measuring two different scores i) the real-time score and ii) the post-trip score. In the final phase of the assessment, a concrete total score is aimed to be evaluated in order to compare directly the safety impact of HADRIAN system innovation to a baseline system.

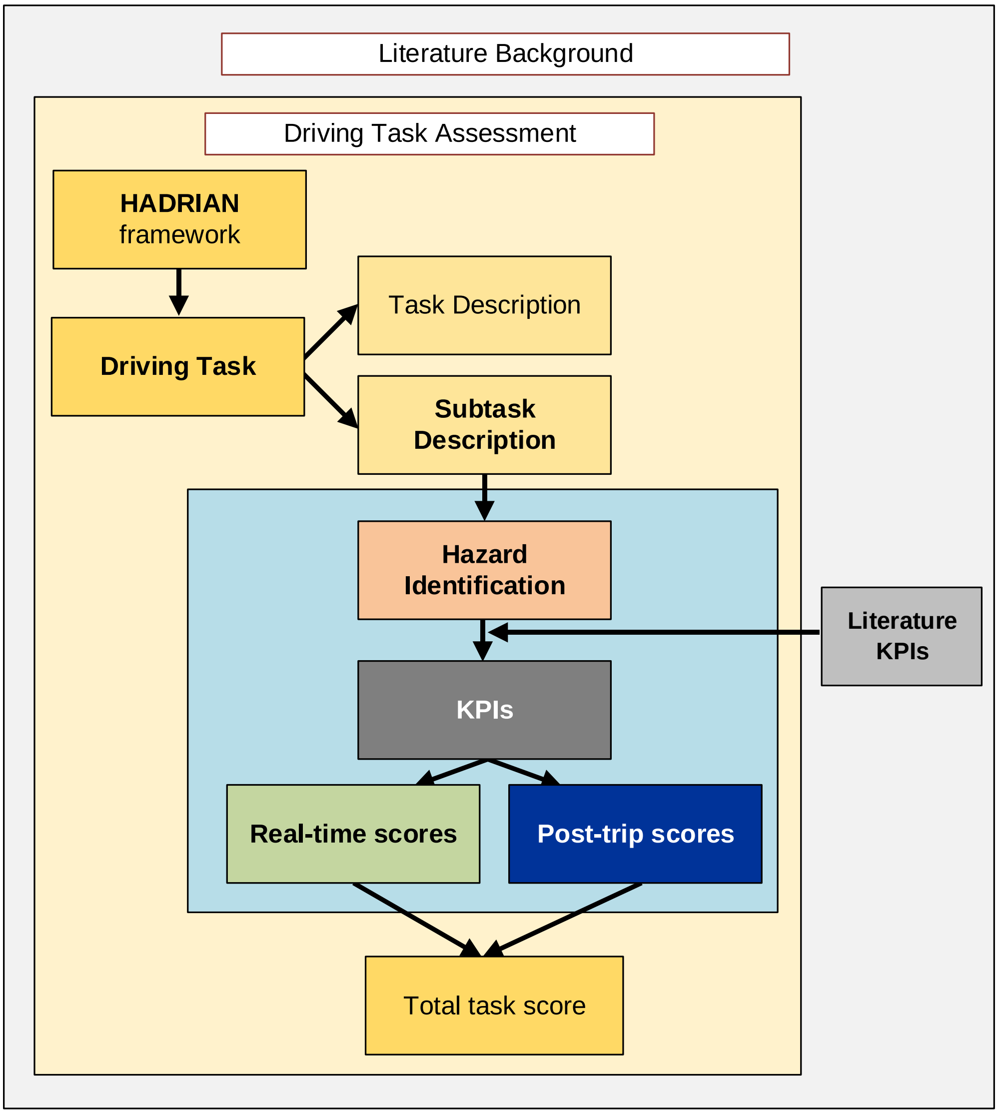

***Figure 2:** Assessing driving tasks within HADRIAN*

2.1 Hazard Identification

The hazard identification was conducted by identifying all possible hazards into the planned driving scenarios that the HADRIAN HMI is tested. The driving scenarios consist of three use cases, namely an elderly driver, a truck driver, and an office worker driver, as mentioned before. Additionally, for each driving scenario, different HADRIAN innovations and different automation levels are tested.

Hazard identification broke down the operational driving scenarios or tasks into several segments or subtasks. For all the segments, it was essential to define the different needs and hazards within the user's driving system, such as driver's and environmental sensing needs, user-centered interaction needs, and safety hazards. As a result, there was a breakdown of the planned driving scenarios, and then the collected KPIs from the literature review (these KPIs are presented in 2.2) were associated in order to investigate if there were capable of assessing the corresponding hazard or need. At this step, many KPIs derived from the literature review were adapted to HADRIAN needs.

For the whole safety and impact assessment, it is vital to explicate the assumptions and innovations of the f-HMI, as they were used in the hazard identification procedure in order to identify missing aspects within the assessment.

Initially, the term "hazard" is the basis of hazard identification. Therefore, its meaning should be analyzed, and hence a representative diagram was created, as shown in **Figure 3**. This aims to investigate more profoundly each potential hazard in the driving scenarios by attempting to find answers to the question "what causes the hazard?". Each hazard consists of three basic components:

- Hazardous Element: This is the basic hazardous resource creating the impetus for the hazard, such as a hazardous energy source such as explosives being used in the system.
- Initiating Mechanism: This is the trigger or initiator event causing the hazard to occur. This causes actualization or transformation of the hazard from a dormant state to an active mishap state.
- Target and Threat: This is the person or thing that is vulnerable to injury or damage, and it describes the severity of the mishap event. This is the mishap outcome and the expected consequential damage and loss.

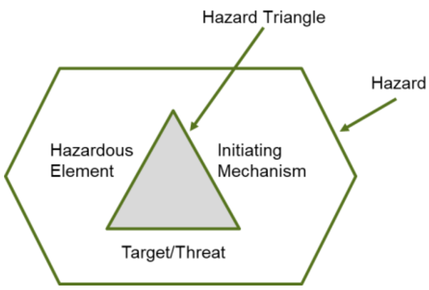

***Figure 3:** Hazard term explanation*

After the explanation of the hazard, the procedure of identifying how the hazard leads to a mishap is explained. A mishap is an actual event that has occurred and resulted in death, injury, or loss. A hazard is a potential condition that can potentially result in death, injury, or loss. The hazard triangle concept aims to conduct the best hazard recognition by evaluating each of its components from a system context, as depicted in **Figure 4**. The state transition between a hazard and a mishap is the hazard triangle, including hazard components and risk factors.

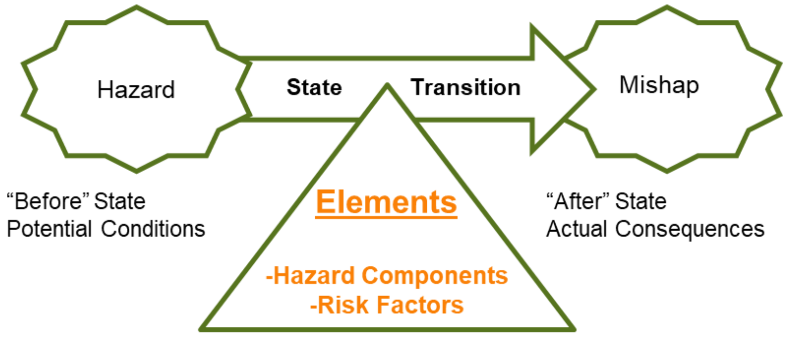

Figure 4: *Hazard and Mishap relation*

The study of the hazard components leads to the study of the hazard causal factors (HCF). HCFs were the basis of hazard identification. HCFs are all the specific items/elements responsible for the presence of a hazard in the investigated system. The HCFs can be divided into categories according to the hazard components (i.e., humans, interfaces, functions, environment, etc.). Therefore, the term system should be explained thoroughly in order to recognize where the hazards can be met.

For several years, the system concept includes only the interrelationship and collaboration between the vehicle and the HMI, as shown in **Figure 5**. On the contrary, in the HADRIAN project, the new system concept was included in the hazard identification as mentioned previously in order to identify relevant multiparametric KPIs on the several hazard components. The "new system concept" is illustrated in **Figure 6**. For each scenario segment and each system element (i.e., the vehicle, HMI, etc.), different hazards were recognized in order to be quantified and subsequently assessed.

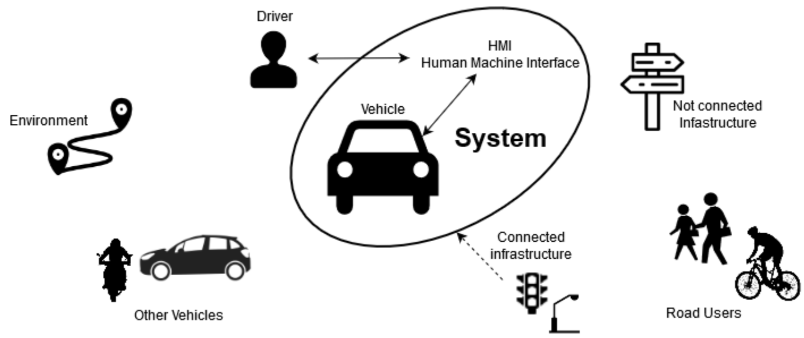

Figure 5: *Conventional concept of "system"*

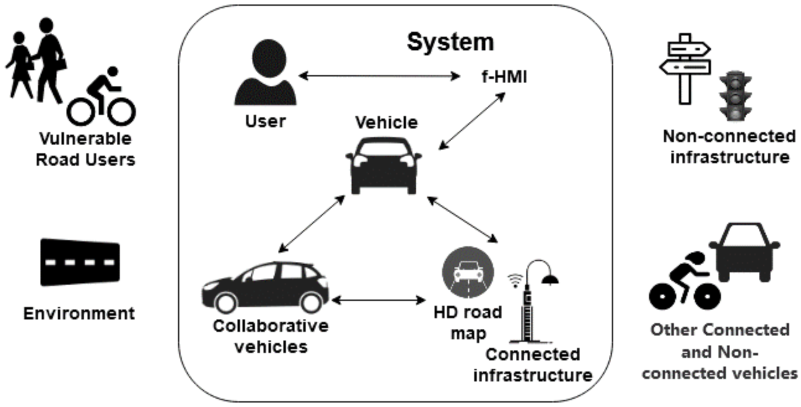

***Figure 6:** New "system" concept*

In the hazard identification, in combination with the new system concept, the following questions were investigated among the driving subtasks, as illustrated in **Figure 7**:

- Vehicle Behaviour: What are the required capabilities of the AVs?
- Driver Role: What is the driver's role inside the vehicle? Which are the expected actions?
- Driver Sensing: What are the motoric and cognitive skills of the driver?
- Infrastructure: What are the infrastructure requirements in the driving environment?
- HMI features: How the communication between driver and vehicle establishes?
- Other vehicle behaviour: The vehicle is in a mixed or full autonomous environment? How are they behaving?

The above questions lead to the below schematic diagram, which shows the elements investigated in the hazard identification procedure and subsequently to the obtained KPIs.

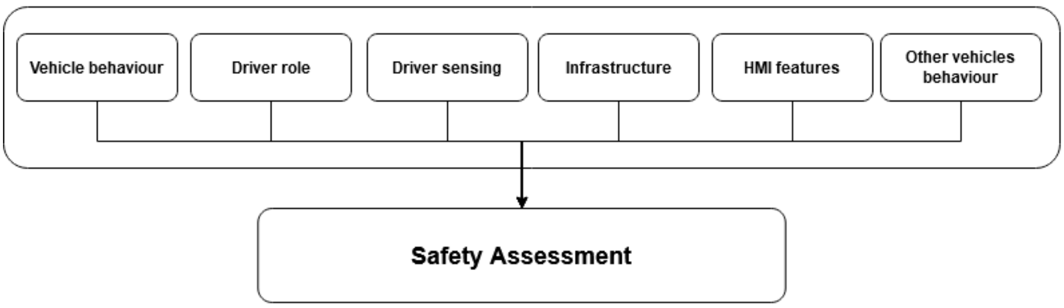

***Figure 7:** Investigated elements in hazard identification procedure*

2.2 Literature Review KPIs

In order to obtain KPIs that are relevant for the HADRIAN use cases and innovations that the project envisions deploying, a literature review was conducted in order to exploit knowledge from previous projects. By exploiting previous project findings, identifying hazards, and focusing on the most crucial risk factors, the KPIs could be used to obtain a score capturing the safety level as well as the general impact of the developed HMI and the innovations that are brought about from the project.

Initially with the purpose of identifying critical KPIs, a literature review was conducted. It consisted of two main steps: i) Literature review on existing KPIs derived from previous research projects, ii) Literature review on existing KPIs derived from generic driving performance and safety metrics. The first literature review focused on reports or deliverables by various research programs with relevant knowledge on AVs safety assessment. The second was conducted using popular databases such as Google Scholar, Science Direct, and Scopus and using specific search terms. The literature review used prioritization criteria for studies published after 2010 and came mainly from Europe and the U.S.

Looking at previous projects, three projects were deemed closer to the purposes of HADRIAN and the use of KPIs. The first one was, the safety and impact assessment performed within the EU - US - Japan Trilateral project (Innamaa et al., 2017). Furthermore, the EU CARTRE project applied KPIs in order to quantify the impacts related to automated driving (Rämä et al., 2018), while the H2020 LEVITATE project applied KPIs in order to quantify the potential impacts on connected and automated vehicles (Elvik et al., 2020).

The reviewed KPIs derived from research programs were categorized into six categories: user-related (which was separated to driving performance, user preference/perception), vehicle-related, safety indicators, infrastructure or network-related, mobility-related, and wider impacts. The criterion of categorization was to create solid categories taking into account as well the elements in the aforementioned new system concept. For instance, a dedicated category was created for the vehicle itself, the user, infrastructure or network, etc. Therefore, each KPI was categorized depending on this criterion. **Table 1** includes the entire list of the obtained KPIs. Amongst the KPIs, there were KPIs that required a subjective answer from users or individuals (e.g., Safety Feeling, Intend to use, Trust of AVs, etc.), and a Likert scale was applied to evaluate these KPIs.

***Table 1:** Reviewed KPIs of the research projects along with their description*

KPIs category	KPIs description
User-related	Driving performance: • Number of take-over instances[1] • Usage of automated driving functions[1, 2] • Average and maximum driving speed[2] • The 95th of percentile speed[2] • Reaction time[2] • Post encroachment time (PET)[2] • Headway time[2] • Number of decelerations due to Vulnerable Road Users (VRUs)[2] • Eco-driving: compare the actual driving with the optimal energy efficient driving style[2]

	User preference/perception: • Comprehensibility of the driving functions[1] • Safety Feeling[1, 2] • Type and duration of in-vehicle activities[1] • User perception of travelling quality[1] • User perception of travelling reliability[1,2] • Adaptability to traffic conditions[2] • Required attention and concentration for driving[2] • Public acceptance and general feeling (i.e., reliable, safe, useful and purpose of the use)[2] • Trust of AVs[2, 3] • Perceived usefulness[2] • Perceived comfort[2] • Feeling of control of the overall situation[2] • Intend to use[2]
Vehicle-related	• Number of take-over instances[1] • Mean and maximum take-over time[1] • Number of emergency decelerations[1]
Safety Indicators	• Number of crashes[1] • Number of emergency take-over instances[1] • Number of conflicts encountered when the TTC (i.e., time to collision) is less than a predefined threshold[1]
Infrastructure or Network-related	• The number of vehicles per hour through a particular road section or intersection, whenever available it can be normalized to the number of lanes and proportion of green lighting time[1] • Maximum road capacity for specific road sections[1] • Peak period travel time along a route[1] • Road capacity[2, 3] • Total or average travel time per road-km[2, 3] • Intersection capacity[2] • Congestion: Delays to traffic[3] • Infrastructure wear[3] • Infrastructure design: Equipping roads with technology for vehicle-to-infrastructure communication[3] • Parking space: Size of areas designated for parking[3]
Mobility related	• Share of transport modes (e.g., car, bike, bus, etc.)[1,2, 3, 4] • Number of trips and trip type[1, 2] • Total duration and distance of trips[1, 2, 3] • Travelling at peak hours: Share of trips made during peak hours[2] • Travelling reliability: Subjective scale or share of trips completed without delays or below a threshold[2] • Travelling comfort: Subjective scale[2,3] • Accessibility of lower density areas: the number of opportunities or activity sites available for people living in the low-density area within a particular travel time or distance[2]

	• Valuation of time: Willingness-to-pay for reduced travel time[3] • Vehicle operating cost: Direct cost for operating a vehicle[3] • Vehicle ownership cost: The cost of buying and keeping a vehicle[3] • Access to travel: The opportunity of taking a trip whenever and wherever wanted[3] • Route choice[3] • Vehicle ownership rate[3] • Shared mobility: Sharing a vehicle with others on a trip-by-trip basis[3] • Vehicle utilization rate: Share of time a vehicle is in motion (not parked); cabin factor (share of seats in use) [3]
Wider Impacts	• Total distance travelled by active modes of transportation (i.e., walking and bicycle)[2] • The proportion of people with improved access to health services[2] • Improved access to recreation and other services[2] • Social isolation: Lack of potential for interactions with other people (subjective or decrease in the number of potential interactions)[2] • Number of injuries[2, 3] and Type of injury (e.g., slight, severe) • Type of conflict[4] • Number of fatalities[2] • Propulsion energy: Source of energy used to move vehicles[3] • Energy efficiency: the rate of loss due to conversion of energy to heat or noise[3] • Vehicle emissions[3] • Air pollution[3] • Noise pollution: Number of individuals exposed to noise above a specified threshold[3] • Public health: Incidence of morbidity and mortality; subjectively rated health state[3] • Employment: Changes in the number of people employed in given occupations[3] • Geographic accessibility: Time used to reach a given destination from different origins[3] • Inequality in transport: Statistics indicating skewness in the distribution of travel behaviour between groups according to social status[3] • Commuting: distance of trips to and from work[3] • Land use: Density of land use for given purposes (residential, industrial, etc.) [3] • Public finances: Income and expenses of the public sector

[1] EU – US - Japan ITS Cooperation Project (Innamaa et al., 2017)
[2] CARTRE project (Rämä et al., 2018)
[3] LEVITATE project (Elvik et al., 2020)
[4] Christoph et al. (2013)

2.3 Method Example

A representative example was generated at the following table (**Table 2**) which explains the procedure of methodological approach as it is explicated in the present section. The first column includes the driving task which was derived from the HADRIAN project, and it is a subpart of the driving scenarios in which the HADRIAN innovations are tested. After the driving task, as can be seen in **Figure 2**, the driving task is separated into task description and driving subtasks. Exploiting the driving tasks, the hazards during driving were identified by the aforementioned hazard identification procedure. After the hazards recognition for each driving task, relevant KPIs, which are capable to capture the enhancement of HADRIAN innovations, were matched considering the literature findings, as explained previously.

Within hazard identification, a comprehensive investigation was carried out by recognizing all components of the hazard, as illustrated in **Figure 3**. For each hazard, the hazardous element, initiating mechanism, and the target/threat were found. This aimed to investigate the transition between the hazard and the mishap, as depicted in **Figure 4**. Furthermore, the identified hazards of this procedure consider hazardous situations that can be encountered in the new system concept, i.e., vehicle, user, HMI, cooperative traffic, and infrastructure. The new system concept was described previously in **Figure 6**. The relevant KPIs consist of literature KPIs (related research projects, driving and safety metrics) and some of them adapted to HADRIAN needs, and additional KPIs were developed with the purpose of assessing the hazards that the literature KPIs were insufficient. In the following section, the relevant KPIs are categorized and presented in an extensive list.

***Table 2:** An example of the Hazard Identification Procedure*

Driving Task	Task Description	Driving Subtasks	Hazard	Relevant KPIs
Harold (the elderly driver) drives on a highway at SAE Level 3. As the end of the automated driving is estimated, the HMI signals Harold to start to take over (start driving manually again). HMI monitors Harold during this time and tells him what to do (to check the speed, the events in front, etc.).	Transition ADL 3 -> Manual & anticipation of system information	• Understanding the signals coming from the system • Reacting to system signals • Transition into manual mode	The takeover time might be not enough.	• Take-over Time
			The operator might provoke an accident.	• Accident Probability • Accident Severity Level • Number of Crashes • Number of Incidents • TTC • Number of Harsh Decelerations
			The operator might get off the road.	• Time-to-Line Crossing (TLC)

Driving Task	Task Description	Driving Subtasks	Hazard	Relevant KPIs
				• Lateral Distance Variation • Lateral Acceleration • Lane Crossings • Number of Hard Shoulder usage
			The operator might feel disoriented.	• Frustration • Mental Workload • Inattention

3. Results

3.1 KPIs grouping

Before merging the exploitable knowledge from literature and the KPIs that were obtained through hazard identification, it was decided to group KPIs into two main categories, namely safety and general impact as presented in **Table 3**. The safety group contains KPIs such as accident or safety risk, driving safety threshold, driver's state, driver's emotions, driving condition, and driver's health. Similarly, in the general impact group, the subcategories were: comfort, acceptance & usability, trust, reliability, and accuracy.

***Table 3:** Subcategories of safety and impact KPIs*

	KPIs subcategory	Definition
Safety	*Accident or Safety Risk*	Measurements that indicate risky or dangerous situations during driving.
	Driving Safety Threshold	Specific driving thresholds which may indicate that the driver is in a risky moment.
	Driver's State	Driver's special condition or state at a particular time (e.g., frustration, mental workload).
	Driver's Emotions	Driver's strong feelings such as anger, stress, etc. that can potentially affect the driving performance.
	Driving Condition	Special external circumstances in the driving environment related to the driving conditions might affect driving performance (e.g., rain, fog, etc.)

	Driver's Health	Issues or impairments that are related to the driver's health and may affect driving performance.
General Impact	*Comfort*	Comfort is when the driver has a pleasant feeling of being relaxed.
	Acceptance & Usability	Acceptance is defined as the willingness of the driver to use the new HMI. Usability is the degree to which it is easy to use the new HMI.
	Trust	Trust is defined as believing that something is safe and reliable.
	Reliability	Reliability refers here to the ability of the fluid interface to provide interventions at least (%) of the time.
	Accuracy	Accuracy means that this intervention is appropriate at least (%) in the case of an intervention carried out.

3.2 Final list of considered KPIs

The final list of KPIs was included in **Table 4.** Along with the description of the KPIs, the type of required measurement data are defined as well as the corresponding units.

Table 4: *Final KPIs list for safety and impact assessment*

KPI	**KPI Description**	**Type of Required Data**	**Units**
	Accident or Safety Risk		
Accident Probability	Accident probability	Driving Data	Probability
Accident Severity Level	Accident severity level regarding the following categories: a)Non-Injury, b)Minor Injury, c)Major Injury, d)Fatal	Driving Data	Categorical
Number of Crashes	Number of crashes in total or per km	Driving Data	Count
Number of Incidents	Number of incidents in total or per km (excluding crashes)	Driving Data	Count
TTC	Number of times when TTC (time to collision) is below 1 sec	Driving Data	Count
Number of Harsh Decelerations	Number of hard brakings (harsh decelerations) in total or per km (or hour)	Driving Data	Count
Number of Pedestrian Incidents	Number of instances when not reacting to a pedestrian appropriately (% of all pedestrians events)	Driving Data	Count
Number of Cyclists Incidents	Number of instances when not reacting to a cyclist appropriately (% of all cyclists events)	Driving Data	Count
Number of Hard Shoulder usage	Number of instances using the hard shoulder	Driving Data	Count
Number of Unexpected Take-overs	Number of unexpected take-overs due to unexpected events (in total or per km)	Driving Data	Count
	Driving Safety Threshold		

KPI	KPI Description	Type of Required Data	Units
Brake Reaction Time	Brake reaction time	Driving Data	S
Take-over Time	Duration of take-overs (in total or per km)	Driving Data	S
Reaction Time	Reaction time in general (excluding braking situation; e.g., accelerating when the traffic light turns greens)	Driving Data	S
Headway Time	Headway Time between the front and the following vehicle passing the same point.	Driving Data	S
Time to Collision	Time to Collision: "The time until a collision between the vehicles would occur if they continued on their present course at their present rates." (Mahmud et al., 2017).	Driving Data	S
Time-to-Accident	Time-to-Accident: "the time that remains to an accident from the moment that one of the road users starts an evasive action if they had continued with unchanged speed and directions" (Mahmud et al., 2017).	Driving Data	S
Margin to Collision (MTC)	Margin to Collision: "Ratio of the summation of the inter-vehicular distance and the stopping distance of the preceding vehicle divided by the stopping distance the following vehicle."(Mahmud et al., 2017).	Driving Data	Ratio
Crash Potential Index (CPI)	Crash Potential Index: "Probability that a given vehicle Deceleration Rate to Avoid a Crash (DRAC) exceeds its maximum available deceleration rate (MADR) during a given time interval." (Mahmud et al., 2017).	Driving Data	Probability
Time Integrated TTC (TIT)	Time Integrated TTC: "Integral of the TTC-profile during the time it is below the threshold" (Mahmud et al., 2017).	Driving Data	S^2
Post Encroachment Time (PET)	Post encroachment time (PET): "The time between the moment that a road user (vehicle) leaves the area of a potential collision and the other road user arrives collision area." (Mahmud et al., 2017).	Driving Data	S
Time-to-Line Crossing (TLC)	Time-to-line crossing	Driving Data	S
Lateral Distance Variation	Lateral position variation (st. dev. of distance from the center of the lane)	Driving Data	M
Lateral Acceleration	Acceleration in general and during lane change	Driving Data	M/S^2
Lane Crossings	Number of lane crossings	Driving Data	Categorical

KPI	KPI Description	Type of Required Data	Units
Distraction	Count and duration of observations that the driver had involved in a distraction task (distinguished for each type) or Distraction measurement with an eye tracker	Driving Data	Count
Motion Sickness	Motion sickness test: 4 point Simplified Simulator Sickness Questionnaire (SSSQ)	Survey	Scale
Frustration	Feeling of frustration (rated by a Likert scale, i.e., 1–9, low–high) or NASA Task Load Index (NASA-TLX) or Frustration test: Posture information (with distance sensors) or facial expressions	Survey	Scale
Mental Workload	Mental workload: NASA Task Load Index (NASA-TLX) or Likert Scale	Survey	Scale
Inattention	Inattention: question with Likert-type scale (0-10)	Survey	Scale
Quality of Takeover	Quality of drivers reaction to a take-over request	Survey	Scale
	Driver's Emotions		
Impatience (Time Pressure)	Feeling of impatience (rated by a Likert scale, i.e., 1–9, low–high)	Survey	Scale
Aggressiveness	Feeling of aggressiveness rated by a Likert scale, i.e., 1–9, low–high or Propensity for Angry Driving Scale (PADS), Driving Anger Scale (DAS), Driving Anger Expression Inventory (DAX), Trait-anger (T-Ang), Australian Propensity for Angry Driving Scale (Aus-PADS)	Survey	Scale
Boredom	The feeling of boredom (rated by a Likert scale, i.e., 1–9, low–high)	Survey	Scale
Stress or	Feeling of stress (rated by a Likert scale, i.e., 1–9, low–high)	Survey	Scale
Stress	Stress measured with Heart Rate Variability (HRV), Electrocardiograph (ECG), Heart rate variability (HRV), Contact sensor PMIC (Heart Rate Information Extracted)	Driving Data	Heart Measurement
	Driving Condition		
Visibility Length	Number of dangerous instances due to reduced driving visibility (in total or per km)	Driving Data	Km
Travel Time per road	Total (or average) travel time per road-km (Time/road-km)	Driving Data	S/Km
Road Capacity	Road Capacity/ flow (Vehicles/hour)	Driving Data	Veh/H
	Driver's Health		
Peripheral Vision	Number of dangerous instances due to reduced peripheral vision	Driving Data	Count

KPI	KPI Description	Type of Required Data	Units
Vision Loss	Number of dangerous instances due to vision impairments	Driving Data	Count
Hearing Loss	Number of dangerous instances due to hearing impairments	Driving Data	Count
Joint Flexibility	Number of instances due to reduced joint flexibility	Driving Data	Count
Comfort			
Comfort	Driver perceptions of travelling comfort (rated by a Likert scale, i.e., 1–9)	Survey	Scale
Number of Take-overs	Number of take-overs instances (in total or per km)	Driving Data	Count
Attention Required	Number of events that the driver needs to pay attention to (number of events in total or per km)	Driving Data	Count
Pressure Feeling	Feeling of pressure in general (measured with Likert scale)	Survey	Count
Acceptance & Usability			
Acceptance	Driver perception of acceptance (rated by a Likert scale, i.e., 1–9, low–high)	Survey	Scale
Usability	Driver perception of usability (rated by a Likert scale, i.e., 1–9, low–high)	Survey	Scale
Comprehensibility	Driver perception of f-HMI comprehensibility (rated by a Likert scale, i.e., 1–9, low–high)	Survey	Scale
Types of Travelers	Types of travelers able to use the vehicle	General Population Survey	Categorical
Intend to Use	Rate the intend to use more often using a scale (i.e., Likert)	Survey	Scale
Trust			
Trust	Trust of HMI (rated by a Likert scale, i.e., 1–9, low–high) or a modified version of the NASA-TLX	Survey	Scale
Control Feeling	Feeling of being able to control the vehicle (rated by a Likert scale, i.e., 1–9, failure-perfect)	Survey	Scale
Unexpected Incidents	Number of unexpected incidents of the car or f-HMI (in total or per km)	Driving Data	Count
Alertness	Driver alertness during driving	Survey	Scale
Safety Feeling	Feeling of safety (rated by a Likert scale, i.e., 1–9, very dangerous – very safe)	Survey	Scale
Travel Quality	Driver perception of travelling quality (rated by a Likert scale, i.e., 1–9, low–high)	Survey	Scale
In-vehicle Activities	Type and duration of in-vehicle activities during high levels of automation	Driving Data	Categorical, S
Reliability			

KPI	KPI Description	Type of Required Data	Units
Reliability	Reliability = (Number of times that HMI intervened) / (Total number of needed interventions)	Driving Data	%
f-HMI Reliability	Driver perceptions of f-HMI reliability (rated by a Likert scale, i.e. 1–9)	Survey	Scale
	Accuracy		
Accuracy	Accuracy = (Number of times that HMI intervened appropriately) / (Total number of needed interventions)	Driving Data	%
Inappropriate Functions	Number of inappropriate events of automated (or HADRIAN f-HMI) driving functions (in total or per km)	Survey	Count

Looking at the safety KPIs group, it can be observed that special focus is given on take-over time and number of take-overs, as these will ensure seamless interaction between the user and the vehicle, as well as headway time, TTC, and the number of harsh events in order to ensure a safe and smooth travel within an automated vehicle. On the same principle, within the general impact group, the most significant KPIs are envisioned to be comfort, safety feeling, required attention as well as trust because these will lead to more acceptable and reliable interactions and driving.

Nevertheless, this list of safety and impact KPIs is only the basis to capture the enhancement that new HMIs would need to prove. Furthermore, additional KPIs can be introduced at later stages of the project by exploiting data from field or simulation trials. Additionally, a thorough validation of the existing KPIs in field trials from the three different use cases (i.e., an elderly driver, a truck driver, and an office worker driver) should shed more light on the safety performance and acceptability of new HMIs.

4. Conclusions

This study attempted to identify critical KPIs capable of assessing the safety and general impact of fluid interactions between the user and the HMI within automated vehicle applications. More specifically, this study investigated and reviewed safety, driving performance, and general impact indicators. 64 KPIs were identified in total as the most significant for the safety and impact assessment of new HMIs for automated vehicles and were categorized into two main categories: safety and general impact, based on exploitable knowledge from previous projects and literature, and a hazard identification procedure.

The obtained KPIs could guide stakeholders in optimizing the safety assessment procedures for human-centered autonomous vehicles. By investigating the list of the 64 KPIs, policymakers could also identify the most critical for specific applications. Nevertheless, the necessary measurements and data need to be defined and validated both in simulation as well as field trials before practical application of the safety and impact assessment is feasible.

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