Impact Assessment of a novel Human-Machine Interface Prototype: A descriptive analysis from the HADRIAN project

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Abstract

The present study was inspired by the HADRIAN project and aims at investigating the impacts of innovative Human-Machine Interface (HMI) prototypes on safety, driving performance and drivers' perceptions using driving simulator and questionnaire data. For this purpose, driving simulator experiments were conducted within the framework of the project in order to test if HADRIAN HMI innovations are safer and more acceptable for the driver. More specifically, this study focuses on a driving simulator experiment that tested innovative HMI prototypes that enhance Automated Driving (AD) SAE Levels 2 or 3. An "HADRIAN-tailored" safety and impact assessment methodology was developed using special Key Performance Indicators (KPIs). Descriptive statistics for the aforementioned KPIs were created in order to perform comparisons and prove the safety and impact advancements.

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

1. Introduction

Road crashes pose a severe threat to public health, ranking as the 8th leading cause of death worldwide with around 1.3 million fatalities annually and a much higher number of non-fatal injuries (20-50 million) (WHO, 2021). The economic cost of these accidents is substantial, with estimates ranging from 0.7 to 3.0 million Euros for preventing a fatality in 31 European countries in 2005 (Wijnen et al., 2019). Moreover, European road accidents cost between 0.4% and 4.1% of GDP, while globally, the WHO estimates the total cost at around 3% of GDP, underscoring the significant impact of road crashes on public health, society, and the economy (WHO, 2018; Wijnen et al., 2019; Yannis et al., 2014). Examining the root causes of road crashes is crucial for addressing this public health issue. It is estimated that human factors account for up to 94% of all road accidents (NHTSA, 2015). However, newer technologies in the automotive sector are anticipated to be safer. In general, transportation systems are anticipated to undergo a significant transformation due to the introduction of Autonomous Vehicles (AVs) (Elvik, 2021; Fagnant & Kockelman, 2015). Specifically, high market penetration rates of AVs are anticipated to improve road safety by reducing human error. Additionally, prior to highly automated vehicles, intermediate SAE automation levels will still require human interactions with the vehicle. In order to realize this, Human-Machine Interfaces (HMIs) are anticipated to be crucial in fostering cooperation between users and vehicles. This was the main subject of the EU H2020 HADRIAN (**H**olistic **A**pproach for **D**river **R**ole **I**ntegration and **A**utomation Allocation for European Mobility

Needs) project, which aimed at providing seamless and fluid interactions between the driver and the automated vehicle.

The main goal of this study is to investigate descriptive insights into KPIs by the developed methodology for assessing new types of HMIs for automated vehicles. The study was conducted within the EU H2020 HADRIAN project. The driver role for automated vehicles is also investigated and assessed using a holistic user-centered approach that evaluates the safety and perceived impact effects with the total aim to achieve high impact and wide-reaching acceptance of automated vehicles.

2. Methodology & Results

The present study was inspired by the HADRIAN project and aims at assessing the impacts of innovative HMI prototypes on safety, driving performance and drivers' perceptions using driving simulator and questionnaire data. For this purpose, driving simulator experiments were conducted within the framework of the project in order to test if HADRIAN HMI innovations are safer and more acceptable, useful, and comfortable for the driver. More specifically, this study focuses on a driving simulator experiment that tested innovative prototypes that enhance Automated Driving (AD) predictability, availability, and continuity, and boost driver monitoring, HMI adaptiveness, and tutoring using Heads Up Display (HUD), LED strips, haptic cues on the steering wheel, and an interactive tablet. Simulated driving scenarios included driving sections with Automated Driving Levels 2 or 3 or manual and in parallel, they were instructed to perform a secondary task. Furthermore, an "HADRIAN-tailored" safety and impact assessment methodology was developed using special Key Performance Indicators (KPIs). The estimation of these KPIs is obtained through driving metrics using the driving simulator and subjective measurements with questionnaires. 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 (Figure 1 & Table 1). Descriptive statistics were developed in order to perform comparisons and prove the safety and impact advancements of the HADRIAN system.

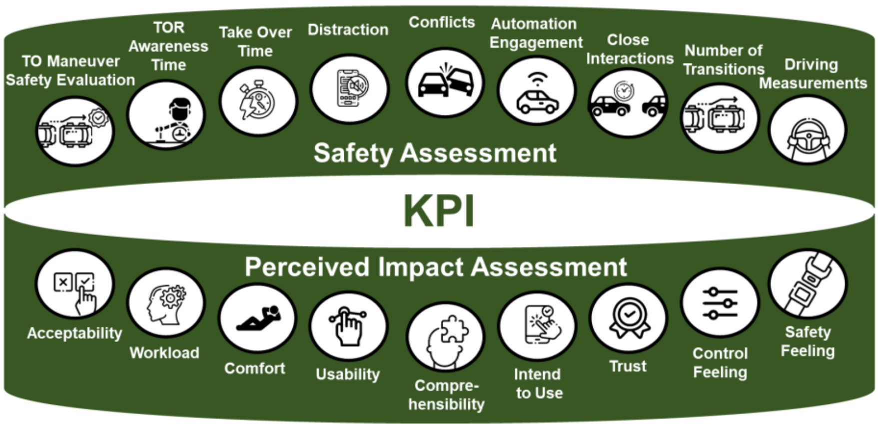


Figure 1: *Set of developed KPIs for safety & impact assessment of HADRIAN innovations*

Table 1: *KPI list for safety & impact assessment of HADRIAN innovations*

KPI ID	***KPI***
KPI 1.1	Take Over Maneuver Safety Evaluation
KPI 1.2	Take Over Request Awareness Time

KPI 1.3	Take Over Time	
KPI 1.4	Distraction	
KPI 1.5	Conflicts	
KPI 1.6	Automation Engagement	• Level 2 • Level 3
KPI 1.7	Close Interactions	
KPI 1.8	Number of Transitions	• AD → Manual • Manual → AD
KPI 1.9	Driving Measurements	• Speeding Duration • Speed Over the Limit • Harsh Cornerings • Harsh Brakings • Harsh Accelerations
KPI 2.1	Acceptability Ratings	
KPI 2.2	Subjective Workload	
KPI 2.3	Comfort	
KPI 2.4	Usability	
KPI 2.5	Comprehensibility	
KPI 2.6	Intend to Use	
KPI 2.7	Trust	
KPI 2.8	Control Feeling	
KPI 2.9	Safety Feeling	

The background as well as the development of this assessment methdoogloy was given to past deliverables of the project (https://hadrianproject.eu/results/) and previous publications related to; i) the identification of risk factors that are connected with HADRIAN use case drivers i.e., elderly, truck and office worker by conducting a literature review in light of automated driving (Sekadakis et al., 2022a, 2022b), ii) the practical considerations and HADRIAN indicators that are used in the safety and impact assessment for seamless interactions through human-machine interfaces, also, in this paper the need for collaboration between academia and industry is highlighted (Sekadakis et al., 2022c), and iii) the presentation of the initial extensive list of Key Performance Indicators that were obtained for safe fluid interactions within automated vehicles (Sekadakis et al., 2021), and iv) the safety implications in the context of "Trustworthy Automated Driving through Increased Predictability: A Field-Test for Integrating Road Infrastructure, Vehicle, and the Human Driver" (Moertl et al., 2022).

2.1 Integrated fluid HMI

For the driving simulator experiment, 20 participants drove with a baseline HMI and 19 with a HADRIAN HMI titled "Integrated fluid HMI". To fully comprehend the assessment outcomes, it is necessary to provide an overview of the study description. The HMIs were tested in the driving simulator of "Virtual Vehicle". The HMI with all the developed HADRIAN innovations aimed to provide a better automated driving predictability, availability, and continuity. The key feature here is that 5 seconds were granted for take over in ADL2 and 15 seconds for take over in ADL3, and that for ADL3 the duration can be predicted through road infrastructure integration. With driver monitoring (i.e., by tracking eye movements to determine visual distraction, and tracking hands-off-wheel with a camera) it shall be ensured that unsafe driver states are detected, while tutoring before the drive (tutoring video) and during the drive (through verbal guidance and feedback and the possibility to repeat tutoring video chapters in ADL3) aims at teaching the driver how to better use the automated driving functions and driver's responsibilities in different driving modes. This all adds to an adaptive human-computer interface, which adapts to the driver states and needs by providing tailored information, feedback, and alerts.

Hence, the integrated fluid HMI encompasses the following key functionalities:

- 5 seconds time for take-overs in ADL2, 15 seconds time for take-overs in ADL3: the countdown information is displayed to the driver
- Ensured time interval in which ADL3 driving is possible: the duration is displayed to the driver
- Tutoring video before the drive, outlining the driving functions, correct system use, and driver responsibilities
- Verbal guidance and feedback for system use and adaptive tutoring during the drive based on gazing behaviour and take-over time during a take-over
- Warnings in case of detected visual distraction or hands-off-wheel during manual or ADL2 driving with times adapted to the driving mode
- Take-over support by providing countdown-information, current speed limit, and information about upcoming obstacles, as well as haptic cues at the steering wheel
- Information about vehicle behaviour in ADL3 (current speed, detected speed limit, upcoming manoeuvres)
- Support of mode awareness, mode changes, and warnings with ambient lighting

In the design of the integrated fluid HMI, these functionalities were addressed by implementing and integrating different interfaces, which serve a specific purpose within the HMI (Figure 2 provides an overview of the components and the setup in the driving simulator used for the experimental study).

***Figure 2:** Components of the integrated fluid HMI of the VIF holistic study*

Furthermore, apart from the HADRIAN HMI, the baseline HMI is a critical component of this assessment methodology for comparing the HADRIAN HMI with other baseline or “state-of-the-art” developments. The baseline HMI has been defined as the system against which all HADRIAN fluid-HMIs were evaluated. To establish the baseline HMI, the following setup was carefully considered and rigorously tested by the Virtual Vehicle driving simulator. For a fair comparison, in the baseline condition, it was assumed the same take-over times between the HADRIAN condition and the baseline condition for ADL2 and ADL3. These were 5 seconds for ADL 2 and 15 seconds ADL3. However, in the baseline condition, these times were not indicated by the HMI. Also, since this is common in modern cars with driving assistance, a hands-off-wheel warning would be provided when driving in ADL2. Similar to the fluid HMI, a warning would be issued if the driver put his hands off the wheel for more than three seconds. Other than that, no adaption to the driver state was provided and no tutoring was available. In Figure 3, the key features of the baseline HMI are indicated.

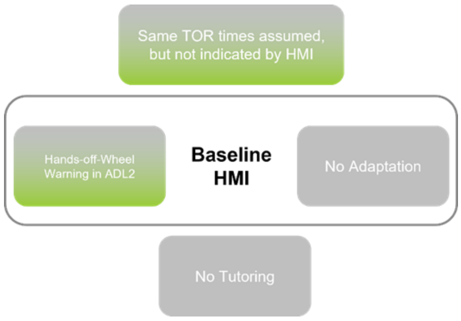


***Figure 3:** Key features of the baseline HMI*

The findings from the implementation of the HADRIAN-tailored safety and impact assessment on data from this simulator study are fully reported in the subsequent subsections.

2.2 Safety KPIs

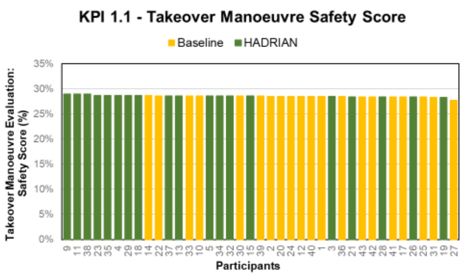
The **driving objective safety KPIs**, namely KPI 1.1 **-** 1.9, have been graphically represented in Figure 4 and are presented in the current section. The graphs showcase the participants' performance, with different colours for the different driving conditions, i.e., Baseline HMI in yellow and HADRIAN HMI in green. The x-axis represents the participants' ID, while the y-axis displays the values of the corresponding driving KPIs. The data points are sorted either in ascending or descending order (depending on the safety effect) based on the KPI values of each participant. The graph visualizes the changes in performance on the KPIs, highlighting observed improvements and/or trend that may have arisen as a result of the HADRIAN innovations. Additionally, three pie charts are provided to display the total number of harsh cornering events, harsh braking events and harsh acceleration events, differentiated also by different colors to represent Baseline and HADRIAN conditions.

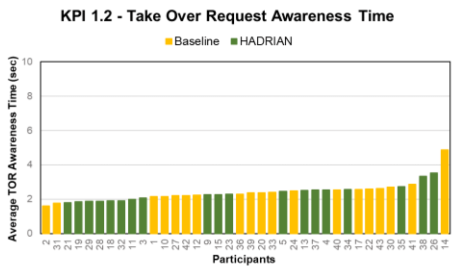
For **KPI 1.1** "Takeover Manoeuvre Safety Score", all participants show a similar maneuver score without great variability but with a higher trend to be observed for HADRIAN conditions. This can be attributed due to two main reasons i) situational awareness of the driver prior to take-over request and ii) support during the take-over maneuver phase. In HADRIAN conditions, the situational awareness of the driver prior to take-over request is presented higher; participants are well informed and prepared about the upcoming maneuver due to the tutoring video prior to the simulation experiment as well as the system informs the drivers for the remaining time until the takeover request. Additionally, during the takeover maneuver phase, the HADRIAN system supports the driver with indicating the upcoming obstacles, the current speed limit, as well as haptic cues at the steering wheel. The state of the driver as well as the driving support during take-over predisposes and supports the drivers to perform a smoother takeover maneuver with lower harsh accelerations and brakings as well as less frequent speed exceedance. For **KPI 1.2** "Take Over Request Awareness Time", “Baseline” participants exhibit an increasing trend, while HADRIAN participants present lower "Take Over Request Awareness Time" values. This could be attributed to the countdown information to the driver (5 seconds for ADL2 and 15 seconds for ADL3) accompanied by the tutoring video, the LED indication and the verbal guidance and feedback, allowing drivers to assess all the required insights from the driving environment in less time. Due to the aforementioned improvements, in the same context **KPI 1.3** "Take Over Time", the HADRIAN participants present a higher trend, which could be explained by the longer available time for reaction and therefore takeover in HADRIAN conditions. Therefore, the HADRIAN driver is not surprised by the takeover request and exploits the majority of the given takeover time compared to baseline conditions. A longer time for take-over is highly beneficial for the driver in order to fully assess optimally the driving environment and conditions prior to the takeover.

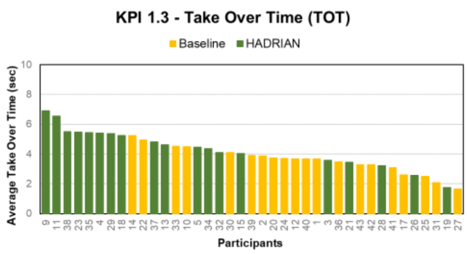
Combining KPIs 1.1, 1.2, and 1.3, the beneficial effect of HADRIAN conditions on **takeover performance** is proven. Not only the driver is more prepared for a takeover request from automated to manual driving with a longer takeover time but, with the indications from the developed system, the driver takes less time to scan the necessary information from the driving environment in order to react appropriately prior to the takeover. Furthermore, the HADRIAN supports the drivers to perform a smoother takeover maneuver with reduced values in speed, acceleration, and braking.

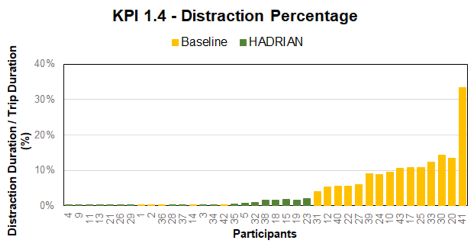
For **KPI 1.4** "Distraction Percentage", Baseline participants display significantly higher distraction values, implying a direct effect of warnings of detected visual distraction or hands-off-wheel in HADRIAN conditions. For **KPI 1.5** "Number of Conflicts", participants demonstrate approximately similar values in both conditions, classified in 4 sets (0, 1, 2 and 3 conflicts). There are not any significant differences between Baseline and HADRIAN conditions and this could be observed since there is no specific system studied for reducing headways and consequently TTC. For **KPI 1.6** "ADL2 Duration" and KPI 1.6 - "ADL3 Duration", similar values are observed for the whole dataset with a lower trend for HADRIAN participants, which can be explained due to the fixed ADL2 and ADL3 scenarios in this study. Also, the values for the **KPI 1.7** "Frequency of TTC <3s" demonstrate similar values in both conditions, classified in 3 sets (1, 2, 3 TTC events). Likewise the KPI 1.5, the absence of a specific system for reducing headways could produce this result.

For **KPI 1.8** "Number of Total Transitions", "Number of Takeovers" and "Number of Manual to AD Transitions", there are not many differences in total transitions per km, as there are fixed transitions in both conditions. HADRIAN participants show a slightly higher trend, which could be attributed to the design of the HADRIAN simulation. For **KPI 1.9** "Speeding Time" and "Average Speed over the Limit", both conditions demonstrate similar distributed values with HADRIAN participants tending to present higher values. The information about current speed and detected speed limit may not be effective for driver behavior. For **KPI 1.9** "Harsh Cornering Events" and KPI 1.9 - "Harsh Acceleration Events", there are no noticeable differences in the total number of events, while for KPI 1.9 "Harsh Braking Events", more events are recorded under HADRIAN conditions. HADRIAN drivers may have responded more aggressively in braking due to the indications of speed in the developed HUD.









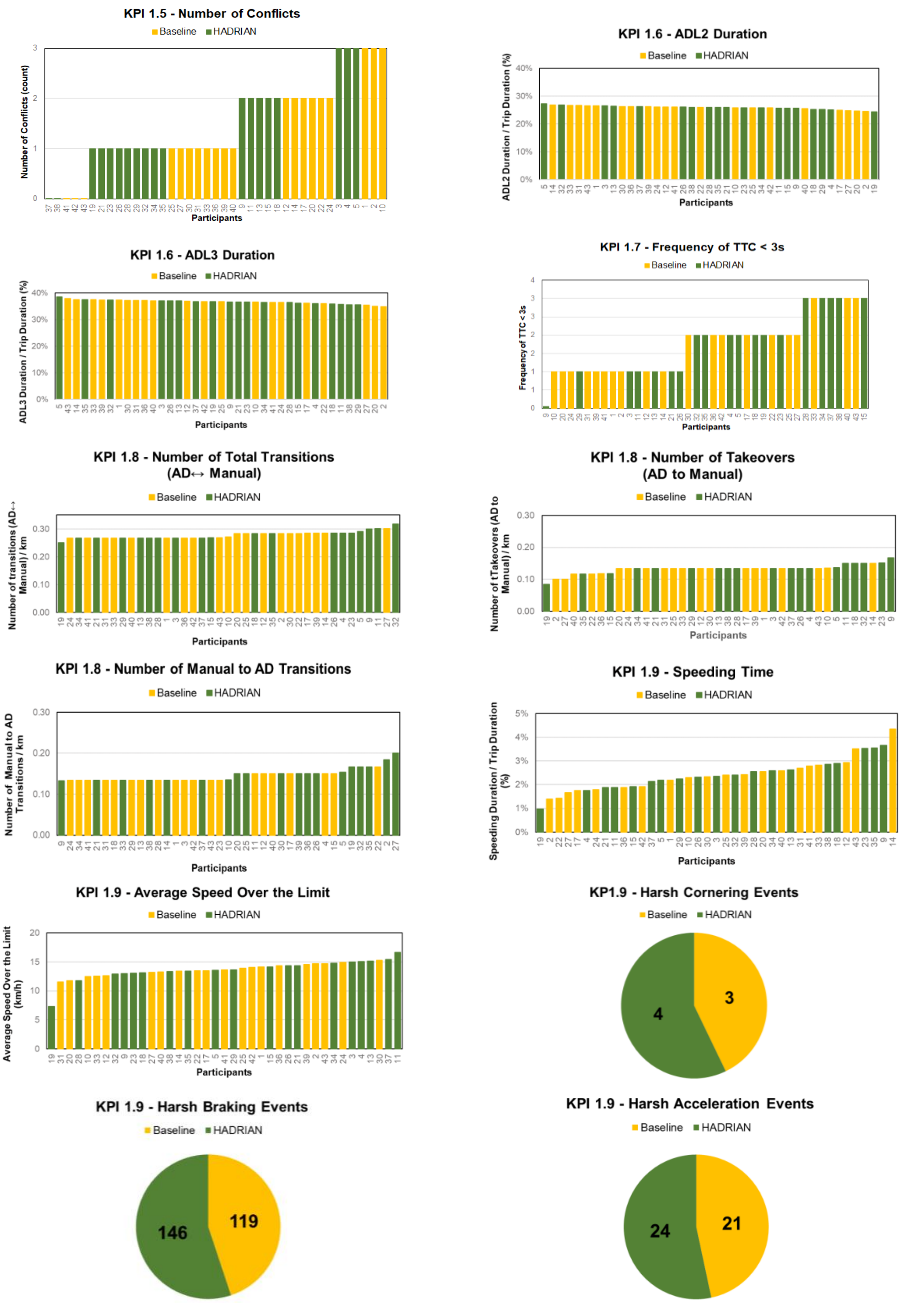


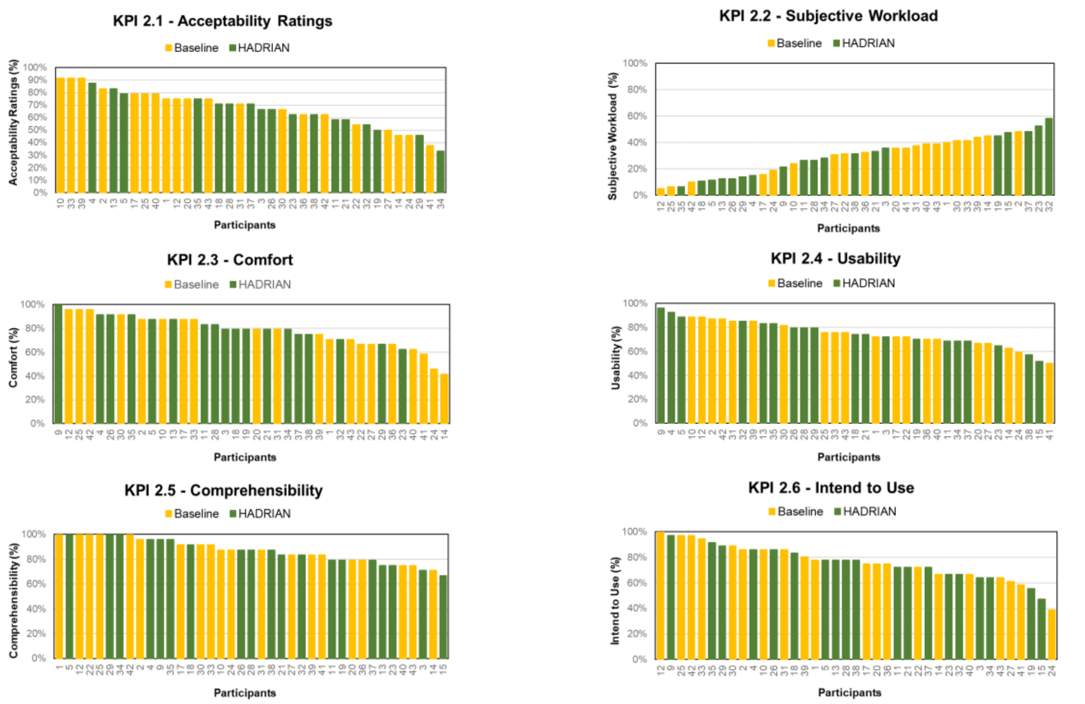
***Figure 4:** Driving objective safety KPI values per condition for each participant*

2.3 Perceived impact KPIs

Similarly to the previous section, the driver **perceived impact KPIs**, namely KPI 2.1 - 2.9 are presented with the following graphs (Figure 5). The graphs showcase the participants' ratings from the filled questionnaires, with different colors for the different driving conditions, i.e., Baseline and HADRIAN. The x-axis represents the participants' ID, while the y-axis displays the values of the corresponding driving KPIs.

For **KPI 2.1** "Acceptability Ratings", a higher preference and acceptance towards the baseline conditions seem to be observed. Participants may have rated the baseline conditions higher compared to the HADRIAN innovations, as they are more familiar with simpler and non-interventive vehicles. Regarding **KPI 2.2** "Subjective Workload", HADRIAN participants seem to rate lower the perceived effort required to operate the driving tasks compared to baseline participants, although few HADRIAN participants rated their driving simulation as the most demanding. This can be attributed to the fact that the applied HADRIAN innovations provide many insights about the driving environment, reducing the driver's mental effort. As for **KPI 2.3** "Comfort" and **KPI 2.4** "Usability", HADRIAN participants are observed to rank slightly higher in their driving experience, denoting that the HADRIAN conditions are more convenient and beneficial to the driving experience.

For **KPI 2.5** "Comprehensibility" and **KPI 2.6** "Intend to Use", HADRIAN conditions seem to be ranked lower compared to the baseline ones. The applied innovations and the amount of information provided may increase the overall complexity and understanding of HADRIAN systems, resulting also in less likelihood of further utilization. For **KPI 2.7** "Trust" and **KPI 2.8** "Control Feeling", HADRIAN participants provided moderately higher ratings to the automated systems compared to the baseline participants. These results reveal the high efficiency of the applied HADRIAN systems in generating a sense of confidence and reliability. For **KPI 2.9** "Safety Feeling" there are not many variations between the two conditions, interestingly the highest "Safety Feeling" values were reported during driving with the HADRIAN HMI.



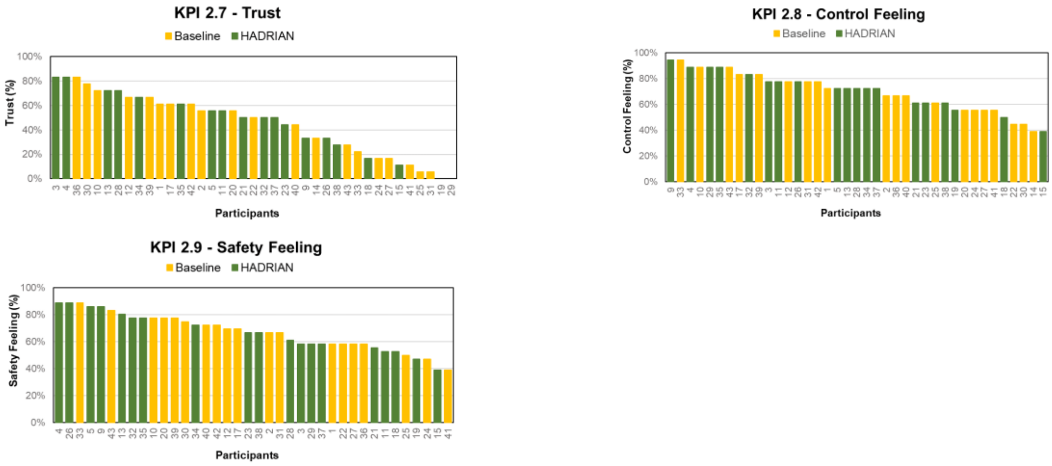


***Figure 5:** Driver perceived impact KPI values per condition for each participant*

2.4 Concluding Results

Figure 4 displays the objective safety KPI distribution among participants of baseline and HADRIAN conditions. Higher differences with a positive effect on safety are depicted in KPI 1.1 "Takeover Manoeuvre Safety Score", KPI 1.2 "Take Over Request Awareness Time", KPI 1.3 "Take Over Time" and KPI 1.4 "Distraction Percentage". HADRIAN innovations, mainly tutoring before and during the simulation, the display of take-over countdown, guaranteed ADL3 time, verbal guidance and feedback, warning, LEDs and eye-tracking system, seem to have a positive impact on driving performance, with reduced take-over request awareness time, increased take over time and reduced distraction percentage. On the other hand, for KPI 1.9 "Speeding Time" and KPI 1.9 "Average Speed over the Limit", participants present a higher trend in HADRIAN conditions, revealing that the applied systems have no direct effect on the speed performance. Similarly, KPI 1.9 "Harsh Brakings" present a negative trend for HADRIAN HMI.

Figure 5 displays the subjective impact of KPI distribution among participants of baseline and HADRIAN conditions. Higher differences with a positive effect on perceived impact are depicted in KPI 2.2 "Subjective Workload", KPI 2.3 "Comfort", KPI 2.4 "Usability", KPI 2.7 “Trust” and KPI 2.8 "Control Feeling". HADRIAN innovations seem to produce participants less mental or cognitive effort, higher convenience in use, more usability and more reliability. On the other hand, the lower values of KPI 2.1 "Acceptability Ratings", KPI 2.5 "Comprehensibility" and KPI 2.6 “Intend to Use” in HADRIAN conditions, demonstrate that the applied systems are still unknown and less accepted to participants.

3. Conclusions

The KPIs that seem to be improved the most, are KPI 1.1 "Takeover Manoeuvre Safety Score", KPI 1.2 "Take Over Request Awareness Time", KPI 1.3 "Take Over Time", KPI 1.4 "Distraction Percentage", KPI 2.2 "Subjective Workload" and KPI 2.8 "Control Feeling". The improvement indicators reveal that the take-over performance prior to and during the take-over maneuver was improved evidently and the distraction is reduced while the declared mental workload of the driver is reduced and the control feeling that the HADRIAN HMI offers is increased compared to baseline HMI. Therefore, results revealed that the investigated HMI prototypes impact the interaction between the driver and the AV for the majority of KPIs and specifically improve significantly a distinct group of important indicators. The aforementioned outcomes were exploited by the HADRIAN project, like any other HMI stakeholder, in order to apply similar human-centered assessment methodologies that evaluates the way human interacts with potential HMI configurations in AVs.

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4. References-Bibliography

Elvik, R. (2021). Can the impacts of connected and automated vehicles be predicted? *Danish Journal of Transportation*, *3*, 1–13. https://levitate-project.eu/wp-content/uploads/2021/02/DJTR-predicting-impacts-CAV.pdf

Fagnant, D. J., & Kockelman, K. (2015). Preparing a nation for autonomous vehicles: Opportunities, barriers and policy recommendations. *Transportation Research Part A: Policy and Practice*, *77*, 167–181. https://doi.org/10.1016/j.tra.2015.04.003

Moertl P., Santuccio E., Solmaz S., Kabbani T., Hartavi A. E., Katrakazas C., Sekadakis M., Zhang H., Letina S. (2022). "Trustworthy Automated Driving through Increased Predictability: A Field-Test for Integrating Road Infrastructure, Vehicle, and the Human Driver", at the Transport Research Arena (TRA) 2022, Lisbon, Portugal (14-17 November 2022).

NHTSA. (2015). *Critical Reasons for Crashes Investigated in the National Motor Vehicle Crash Causation Survey*.

Sekadakis M., Katrakazas C., Clement P., Prueggler A., Yannis G. (2022c). "Safety and impact assessment for seamless interactions through human-machine interfaces: indicators and practical considerations", at the Transport Research Arena (TRA) 2022, Lisbon, Portugal (14-17 November 2022). (c)

Sekadakis M., Katrakazas C., Santuccio E., Mörtl P., Yannis G. (2022b). "A review of risk factors associated with elderly, truck and office worker drivers for automated driving applications", at the 8th Road Safety and Digitization, Athens, Greece (8-10 June 2022). (b)

Sekadakis M., Katrakazas C., Santuccio E., Mörtl P., Yannis G. (2021). "Key Performance Indicators for safe fluid interactions within automated vehicles", at the 10th International Congress On Transportation Research (ICTR), Rhodes, Greece (1-3 September 2021).

Sekadakis, M., Katrakazas, C., Santuccio, E., Mörtl, P., & Yannis, G. (2022a). "Risk factors linked with elderly , truck and office worker drivers : a literature review in light of automated driving". Advances in Transportation Studies, Special Issue, Vol. 3, 95-108. (a)

WHO. (2018). *GLOBAL STATUS REPORT ON ROAD SAFETY 2018*. ISBN 978-92-4-156568-4.

WHO. (2021). *Road traffic injuries*. https://www.who.int/news-room/fact-sheets/detail/road-traffic-injuries

Wijnen, W., Weijermars, W., Schoeters, A., van den Berghe, W., Bauer, R., Carnis, L., Elvik, R., & Martensen, H. (2019). An analysis of official road crash cost estimates in European countries. *Safety Science*, *113*(December 2018), 318–327. https://doi.org/10.1016/j.ssci.2018.12.004

Yannis, G., Papadimitriou, E., & Folla, K. (2014). Effect of GDP changes on road traffic fatalities. *Safety Science*, *63*, 42–49. https://doi.org/10.1016/j.ssci.2013.10.017