Proceedings of the ASME 2024
International Design Engineering Technical Conferences and
Computers and Information in Engineering Conference
IDETC-CIE2024
August 25-28, 2024, Washington, DC

DETC2024-143430

EXPLORING HUMAN-MACHINE INTERACTION IN LEVEL 4 AVS: A STUDY ON TAKE-OVER MANEUVER IN A ROUNDABOUT SCENARIO

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ABSTRACT

Currently, one of the most important challenges in the field of road vehicles concerns the reduction of road accidents and fatalities. The development of new advanced driver assistance or automated driving technologies may contribute to this goal in the future. This research delves into the analysis of Level 4 (L4) automated vehicles (AVs), specifically focusing on the take-over manoeuvre when the AV exits its Operational Design Domain (ODD). It aims to analyse how the take-over changes, considering factors such as the human driver's state, the machine's operation, and the output devices used to alert the driver. To carry out the preliminary tests, an urban road network, including a mini-roundabout, was replicated in the VI-WorldSim environment, and real human drivers experienced the simulation through a dynamic driving simulator. Drivers were assessed qualitatively, using questionnaires to analyse their perception of L4 AVs, and quantitatively, examining the take-over time needed and their heart rate to investigate the physiological response. Preliminary results show that participants perceived the simulation as realistic and immersive, and they reported an ease of use of AVs. Furthermore, physiological data highlighted an increase in heart rate upon the start of take-over, validating the cognitive load of the individual. The study is part of the HL4IT project aimed at supporting the development of Level 4 AVs in an Italian traffic environment.

Keywords: take-over, L4 AVs, driver's state, dynamic driving simulator, roundabout

1. INTRODUCTION

The World Health Organisation estimates that 1190000 road deaths occur worldwide, with more than half among vulnerable road users, including pedestrians, cyclists, and motorcyclists [1]. In 2022, 165889 road accidents happened in Italy, 3159 people died, and 223475 were injured [2]. The human factor plays a pivotal role in car crashes, considering aspects like inexperience, lack of skill, risk-taking behaviours, and visual, cognitive, and mobility impairment [3]. In this context, Automated Vehicles (AVs) and Advanced Driver Assistance Systems (ADAS) are expected to bring benefits like traffic optimization and accidents reduction [4–6]. Conversely, AVs may encounter unexpected and special road conditions that are not able to navigate and require human assistance. For this reason, the human-machine interaction must be explored in both directions. The current trust paradigm, in which the human evaluates the trustness of the vehicle to operate in a given condition, should be questioned, inquiring whether an AV should enable a given driver to regain control of the vehicle or continue directing its operation [7].

This paper focuses on Level 4 (L4) AVs [8] analysis and, more in detail, on the take-over manoeuvre [9], i.e., the transfer of the driving task from the AVs to the human driver. In this manoeuvre, once the AV exits its Operational Design Domain (ODD) [10], it must give back control to the human driver or reach a safe condition, typically stopping itself. During this event, the following aspects should be extensively considered

1. The human driver, its distraction state and previous experience [11, 12];
2. The machine operating the vehicle and its ability to get into a safe condition and properly warn the driver, applying specific techniques such as machine learning [13, 14];
3. The output devices employed to alert the driver [15].

Specifically, this research is part of the Humans with Level 4 automated vehicles in an ITalian environment - HL4IT project, aiming at exploring the human-machine paradigm, supporting the development of Level 4 AVs and representing the majority of Italian traffic environments. This paper describes the first application

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Documentation for `asmeconf.cls`: Version 1.37, May 25, 2024.

of this research: a take-over manoeuvre at an urban roundabout with work in progress and traffic re-routing. As real-world tests to understand driver reactions are impractical for safety and cost reasons, a virtual environment reproducing the scenario is realized, and a dynamic driving simulator is employed.
The paper is organized as follows. Firstly, a brief literature analysis is carried out, and the present research topics and perspectives are highlighted. Secondly, the take-over scenario and the employed driving simulator are presented, and then, the test procedure for the investigation of the human-vehicle interaction is described. Finally, the qualitative and quantitative results of preliminary tests are collected and discussed to understand the utilised framework's effectiveness, the drivers' cognitive load, their general acceptance of the scenario, and future developments.

2. LITERATURE REVIEW

In recent years, transportation demands have increased and pre-existing infrastructures are compelled daily to accommodate heavy and increasing traffic flow, frequently resulting in road accidents and traffic congestion [16]. Hence, the development of autonomous vehicle technology is garnering increasing attention, owing to its ability to smooth traffic flow [17], reduce fuel consumption and pollutant emissions [18, 19], and enhance safety by eradicating the human factor [20, 21]. Indeed, the vast majority of accidents are caused by human errors, frequently resulting from monotonous driving, distraction or overloading attention [22]. Therefore, the human-machine interaction must be cautiously explored, assisting the human driver and flipping the trust paradigm, inquiring whether an intelligent vehicle should enable a given driver to continue directing its operation. [7, 23]
Autonomous vehicles are vehicles equipped with an Automated Driving System (ADS) capable of performing part or all of the Dynamic Driving Task (DDT), which includes all the real-time operational and tactical functions required to navigate a vehicle in the traffic [24]. Six levels of driving automation have been distinguished based on the capability of managing different driving operations. The Society of Automotive Engineers (SAE) provided a taxonomy containing a detailed description of each level [24]. This document defines the Autonomous Vehicles Level 4 as vehicles conceived with high driving automation, capable of performing the entire DDT within their Operational Design Domain (ODD). They can always achieve a minimal risk condition without requiring the driver to intervene, thereby avoiding immediate danger, even if they are not within the ODD.
The ODD represents simply the boundaries of the condition in which each autonomous vehicle can execute its DDT [24, 25]. Therefore, it cannot be defined only through a geographical area. Technological and design limitations must be considered, resulting in environmental, speed and geographical restrictions, as elucidated in the SAE taxonomy. The ODD comprises multiple variables that must satisfy certain design criteria. Consequently, it cannot be regarded as immutable. A change in road type, weather or lighting conditions, or the presence or absence of certain road features may result in exiting from the ODD [24].
When exiting the ODD, the AV L4 can ask the driver to intervene, prompting a Take-Over-Request (TOR) by providing an audible, visual or vibrotactile stimulus [26]. The time available before reaching the automation system limit is called time budget [26]. Within this temporal window, the driver should be capable of regaining vehicle control.
The duration between the take-over stimulus and driver intervention is referred to as Take-Over Time (TOT) [26, 27]. Its value is significantly influenced by numerous factors, such as the stimuli provided and the time budget available.
As defined in [26], the TOT is increased by

- The usage of a handheld device;
- Performing a non-visual task;
- Having eye-closed;
- Available time budget.

Conversely, the TOT decreases when

- An auditory or vibrotactile TOR is provided;
- The TOR can be anticipated.

Authors in [28] assert that frequently employed time budgets are 3s, 4s, 6s, and 7s, with corresponding mean TOT respectively of 1.14s, 2.05s, 2.69s, and 3.04s. However, in vehicles with higher levels of driving automation, the available time budget tends to have a larger duration, leading to a potentially safer and controlled take-over procedure. Indeed, in the literature survey [29], based on the analysis of 17 studies, the authors concluded that 10 seconds appear adequate for enabling the driver to regain control. This viewpoint is also supported by authors in [30], who conducted a test on 44 participants to assess their capability of regaining control by providing a time budget of 10 seconds.
The take-over procedure encompasses several cognitive and motor stages [26]

1. Perception of the auditory, visual or vibrotactile stimuli;
2. Information-processing;
3. Decision making;
4. Regaining control of the situation;
5. Actual action fulfilment.

Given the complex nature of the human being, the monitoring of the driver state is a complex task. Bio-telemetry systems can gather measurements such as Electrocardiography (ECG), Electroencephalography (EEG) and Electrodermal Activity (EDA), thus facilitating the analysis of human-machine interaction in stressful situations [31]. In the context of take-over, the types of warning methods utilized to alert and inform the driver play a crucial role. In [32], the influence of different alert methods on the driver's take-over time and reaction are highlighted. Specifically, voice prompts, earcons, LED lights, and vibrations in the back support and seat can be employed, resulting in different lateral motion control, take-over time, and driver's transient control. Combining visual, auditory, and haptic warning stimuli can improve human behaviour and psychological reaction [33].
If the driver fails or decides not to regain control, the autonomous

vehicle must perform the DDT fallback, attaining a minimal risk condition. In rare and catastrophic situations where this is not feasible, a failure mitigation strategy must be applied, performing an in-place stop.

2.1 HL4IT Project

"Interaction of Humans with Level 4 AVs in an Italian Environment - HL4IT" is a research project that aims to deploy automated mobility in Italy, considering Level 4 AVs [34]. It stems from the necessity of testing the behaviour of AVs in a peculiar scenario, such as the Italian one. Previous studies have only been conducted in countries with different road network configurations, such as Northern Europe and North America. Therefore, three scenarios typical of the Italian context will be selected to assess the driver's ability to regain control in urban, extra-urban, and highway environments.
Specifically, the project's objectives are

- the psychophysiological characterization of the driver, considering both the automated vehicle Level 4 and the Italian environment;
- the definition of an Operational Design Domain suitable for representing 80% of the Italian road network and traffic.

The project is highly multidisciplinary and is tackled by a team composed of mechanical and electronic engineers with the strong support of psychometrics doctors in charge of assessing the reactions and behaviour of human drivers.

3. ROUNDABOUT SCENARIO WITH L4 AVS

In this paper, only the roundabout scenario developed in the HL4IT project is considered. The roundabout has been chosen as one of the most representative scenarios of the Italian road environments. A complete urban network, shown in Figure 1, has been developed, with highways, intercity roads, and an urban mini-roundabout as the main component of the traffic infrastructure. During the simulation, three driving phases are considered

1. *Phase 1 (blue section in Figure 1)*: in the first part of the manoeuvre, the vehicle is an automated vehicle and the human being is not driving. The AV travels from point A in the highway to the roundabout (point B) along the blue path. The driver is asked to use a handy device to watch a video in order to be distracted;
2. *Phase 2 (red section in Figure 1)*: when the AV approaches point B close to the roundabout, the presence of road works altering the ordinary traffic flow causes the vehicle to exit the ODD. At this point, a TOR is triggered and sent to the driver. If the driver takes control within the take-over time budget, they will continue to drive the car, following the directions on the vehicle dashboard to navigate the roundabout, avoiding the road works. In this case, they are asked to exit at the second leg and to avoid the road works they must navigate the roundabout clockwise instead of the usual counterclockwise direction. Otherwise, the vehicle will stop safely, and they will remain inside the cockpit;
3. *Phase 3 (orange section in Figure 1)*: this last section is considered only if the driver accepts the control of the vehicle in the previous phase. In this case, the driver is asked to drive the vehicle from point C back to point A along the orange path. While driving, the driver must comply with ordinary road rules and an auditory signal is activated if the speed limit is exceeded to simulate the warnings that are usually present on the most recent vehicles.

The overall duration of the test is about seven minutes. Clearly, such a complex scenario cannot be safely realized on a real road. For this research, a dynamic driving simulator, specifically the dynamic driving simulator of the DriSMi Laboratory of Politecnico di Milano [35], is employed. The dynamic driving simulator allows the presence of a human in the loop and to study the human-machine interactions in a safe, controlled, and repeatable environment.

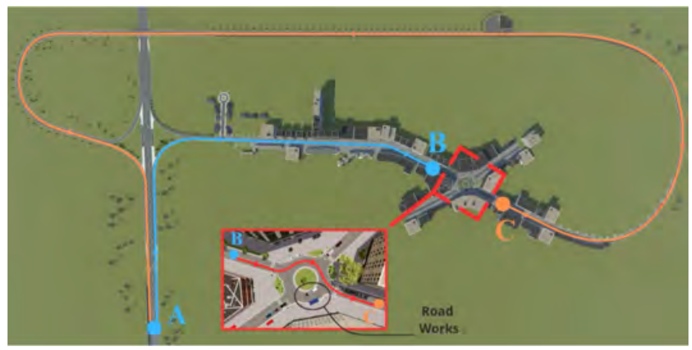

FIGURE 1: Simulation environment created using VI-WorldSim.

3.1 Virtual roundabout environment

The roundabout is a digital twin of a four-leg, single-lane mini-roundabout located in Milan. This roundabout has been selected as it has characteristics representative of most of the Italian urban roundabouts. Specifically

- Two of the legs are central arteries of the city, greatly increasing traffic on the roundabout.
- The roundabout has a standard configuration widely distributed.
- Every leg has pedestrian crosswalks immediately before entering vehicles inside the circulatory roadway.

Figure 2 shows the first-person view of the roundabout model created in the 3D virtual environment VI-WorldSim [36]. On the right, the road works are visible. This makes part of the road inaccessible and forces a different traffic flow. The traffic flow is managed by traffic lights located on the four legs and visible in the right corner of the picture. When the driver has the green light to exit, as requested, at the second leg a temporary yellow signal is present to instruct that the roundabout has to be navigated clockwise.

FIGURE 2: Entrance of roundabout from the driver's point of view.

3.2 Dynamic driving simulator

The tests are carried out by using the dynamic driving simulator (see Figure 3) of the DriSMi Laboratory of Politecnico di Milano [35]. It is a VI-Grade DiM400 [37] high-fidelity cable-driven dynamic driving simulator with redundant degrees of freedom featured by two actuation stages. The first stage consists of a cable-driven platform able to move in the plane and rotate around the vertical axis in the low-frequency range below 3Hz. The second stage consists of a specially designed hexapod with 6 degrees of freedom and able to reach 30Hz. Finally, eight shakers are located at the suspension points for NVH frequencies up to 200Hz. Seat belts, active seat, brake pedal and steering wheel provide haptic feedback. A 270° widescreen shows the graphical environment, and a multichannel sound system provides the auditory feedback. For more information on the dynamic driving simulator, please refer to [38].

FIGURE 3: Dynamic Driving Simulator at DriSMi Laboratory of Politecnico di Milano

3.3 Take-over request signal

A combination of two different sensorial signals is provided to the driver for the take-over request.

- *Visual signal.* A visual signal is displayed on the cockpit dashboard. The visual signal comprises a countdown to inform the driver of the remaining time budget and the instructions on how to request control of the vehicle. If the driver takes control of the vehicle, the countdown is interrupted and is replaced by a map showing detailed road directions. Otherwise, a message to remain in the vehicle is given. The visual take-over request is depicted in Figure 4.
- *Auditory signal.* A soothing female voice is used to convey a verbal request for take-over. The verbal request describes the exceptionality of the request and the necessity to take-over. The request is formulated as follows: "Attention, emergency situation, regain control of the vehicle". The request is repeated until the driver acquires the control of the vehicle or the time budget expires.

FIGURE 4: Take-over request on the vehicle dashboard. A countdown is provided to inform the driver of the remaining time budget, along with instructions on how to request control of the vehicle.

4. PRELIMINARY TESTS

Preliminary tests are performed to acquire the first data on the acceptability of the simulation session. The sample included 8 university students who agreed to participate in the study. Participants had no prior experience with dynamic driving simulators. Two (25.0%) participants were female, and six (75.0%) participants were male; participants' mean age was 24.3 years, $SD = 0.71$ years (min. age = 23 years, max. age = 25 years). Considering participants' educational level, eight (100.0%) participants had bachelor degree; taking into accountant participants' civil status, eight (100.0%) participants were unmarried. Participants' driving experience ranged from 5 to 7 years, $M = 6$ years, $SD = 0.87$. To evaluate the subjective perception of Level 4 AVs, participants were administered self-report measures selected to assess basic personality traits, driving style, general disposition towards AVs, and positive and negative emotions (e.g., sadness, joy). Specifically, the measure to assess general disposition towards AVs was developed in an independent psychometric study involving 730 community participants. These measures were completed before starting the driving experience (i.e., baseline assessment).
Each participant followed the procedure described in section 3. The experimental sessions followed a protocol that was specifically defined to assess the status of the subjects exposed to autonomous vehicle driving. The duration of the different phases shall respect the time necessary for the assessment of the change and shall ensure the necessary data length for the subsequent processing steps. The sequence involves capturing the following intervals: 3 minutes of baseline on board of the simulator, 3-4 minutes of autonomous driving, followed by a take-over phase

(maximum 10s) and a manual driving phase performed by the subject (3-4 min). During the take-over phase, the driver regains vehicle control by pushing both paddle shifters, while the first and last phases are used to let the driver become accustomed to the automatic and manual driving conditions, respectively. Throughout the session, EEG signals (64 channels, Fs=1000Hz) were acquired using the ANT Neuro waveguard^{TM} net, and EDA (2 channels, Fs=500Hz) and ECG signals (3 channels, Fs=500Hz) were recorded using the VI-BioTelemetry system [39]. The aim is to obtain accurate indications of the perceived difference during the take-over action and throughout the simulation and to evaluate changes in physiological control systems as the conditions to which the subject is exposed are changed. At the end of the simulation session, participants completed a post-test psychometric evaluation, including measures of motion sickness, post-test positive and negative emotions, immersiveness of the driving experience, and disposition towards L4 AVs after the driving experience.
It is important to acknowledge that these findings are preliminary because of the small number of participants. Including a broader group of drivers in future studies is advisable to gain more precise insights.

4.1 Psychological tests results

This section collects the results of the preliminary tests. At the baseline, participants showed an average Differential Emotion Scale (DES) Positive Affectivity Scale score (M = 4.40, SD = 0.53) that was significantly higher than the average DES Negative Affectivity Scale score (M = 1.78, SD = 0.63), mean difference = 2.62, SD = 0.96, 2-tailed nonparametric bootstrap p (based on 10000 bootstrap replications) = .003, Cohen's d = 2.72 (nonparametric bootstrap 95% confidence interval for Cohen's d = 1.15, 4.27). Similar considerations held for post-test comparisons between DES Positive Affectivity Scale scores (M = 4.03, SD = 0.81) and DES Negative Affectivity Scale scores (M = 1.70, SD = 0.67), mean difference = 2.32, SD = 1.17, 2-tailed nonparametric bootstrap p (based on 10000 bootstrap replications) = .003, Cohen's d = 1.98 (nonparametric bootstrap 95% confidence interval for Cohen's d = 0.73, 3.19). No significant difference was observed in our study between baseline average score and post-test average score on both DES Positive Affectivity Scale, mean difference = 0.38, SD = 0.90, 2-tailed nonparametric bootstrap p (based on 10000 bootstrap replications) = .30, Cohen's d = 0.42 (nonparametric bootstrap 95% confidence interval for Cohen's d = -0.32, 1.13), and DES Negative Affectivity Scale, mean difference = 0.08, SD = 0.76, 2-tailed nonparametric bootstrap p (based on 10,000 bootstrap replications) = .77, Cohen's d = 0.10 (nonparametric bootstrap 95% confidence interval for Cohen's d = -0.60, 0.79). As a whole, our data suggested that our experimental procedure had no significant impact on participants' perceived positive and negative emotions, at least as they were operationalized in the DES. The descriptive statistics of participants' subjective post-test reports concerning perceived realism of the simulated driving experience, perception of the simulated driving experience, and opinions concerning automated drive vehicles are summarized in Table 1.

As it can be observed, the simulated drive experience was

TABLE 1: Descriptive Statistics of Participants' Post-Test Self-Reports on Perceived Realism of The Simulated Autonomous Driving Experience, Perception of the Simulated Autonomous Driving Experience, and Opinions Concerning Automated Drive Vehicles (*N* = 8).

	n	%
How realistic have you felt the driving experience		
-3 (Definitively Unrealistic)	0	0.0
-2	1	12.5
-1	0	0.0
0	3	37.5
1	2	25.0
2	2	25.0
+3 (Definitively Realistic)	0	0.0
Did you feel completely engaged in the driving experience		
-3 (Completely Disagree)	0	0.0
-2	0	0.0
-1	1	12.5
0	0	0.0
1	4	50.0
2	3	37.5
+3 (Completely Agree)	0	0.0
How did you feel during autonomous drive		
Completely at Ease	1	12.5
Moderately at Ease	5	62.5
Neither at Ease, Nor Uneasy	2	25.0
Moderately Uneasy	0	0.0
Completely Uneasy	0	0.0
How did you feel when the autonomous drive vehicle asked you to take control		
Completely at Ease	2	25.0
Moderately at Ease	2	25.0
Neither at Ease, Nor Uneasy	2	25.0
Moderately Uneasy	2	25.0
Completely Uneasy	0	0.0
How did you feel while driving after taking control of the autonomous drive vehicle		
Completely at Ease	1	12.5
Moderately at Ease	6	75.0
Neither at Ease, Nor Uneasy	1	12.5
Moderately Uneasy	0	0.0
Completely Uneasy	0	0.0
After this driving experience, how do you feel riding an autonomous drive vehicle rather than driving a conventional car		
Completely at Ease	1	12.5
Moderately at Ease	4	50.0
Neither at Ease, Nor Uneasy	2	25.0
Moderately Uneasy	1	12.5
Completely Uneasy	0	0.0

perceived as adequately realistic and immersive by the majority of our participants. Similarly, none of our participants rated the simulated drive experience as uncomfortable, whereas the majority of our participants experienced no difficulties when the simulated autonomous vehicle asked them to take control of the drive. Interestingly, at the end of the experiment, the majority of our participants reported that they would find at ease with riding an autonomous vehicle.

4.2 Take-over results

All participants regained control of the vehicle within the take-over time budget allocated. Table 2 collects the time needed for each driver to take control once the TOR is triggered through auditory and visual outputs.

TABLE 2: Time needed for each driver to regain control of the vehicle once the take-over request has been sent.

Driver	Take-over time [s]
Tester 1	6.908
Tester 2	4.654
Tester 3	3.570
Tester 4	4.662
Tester 5	7.770
Tester 6	4.364
Tester 7	5.002
Tester 8	6.958

4.3 ECG signal analysis

From the ECG signals recorded in the baseline and in the simulation session, QRS complexes were detected based on the steepness of the absolute gradient. R-peaks were then identified as local maxima within the QRS complexes. Artifacts, such as extra, misaligned, or ectopic beats were corrected using the algorithm described in [40] and the outcome was visually inspected to assess its quality. The series of R-R length intervals as a function of beat number (i.e., the heart rate variability (HRV) time series) was constructed. HRV is not uniformly sampled: each value corresponds to the occurrence of an R-peak. Hence, this time series was submitted to a shape-preserving piecewise cubic Hermite interpolating polynomial (PCHIP) and uniformly resampled at 4Hz [41]. The heart rate (HR) time series in beats per minute (bpm) can be obtained from HR[i] = 60/RR[i], where RR[i] is in seconds (s). The mean of the HR time series recorded during the baseline period was subtracted from the corresponding HR time series obtained during the simulation session for each participant. This procedure helps to assess the relative change in the heart rate (ΔHR) for each subject with respect to the one measured during the baseline, assumed as the intersubject reference.

4.4 Preliminary results on HRV analysis

Out of the 8 available subjects, 6 of them were considered. Two subjects (1 male, and 1 female) were excluded due to low ECG signal quality. The HR signals during the simulation session were aligned based on the time corresponding to the start of the Take-Over-Request alarm and the average relative change in the HR signal was computed. Figure 5 reports the preliminary results. Upon the start of the Take-Over-Request alarm, a noticeable increase in ΔHR can be observed with consistency across the subjects.

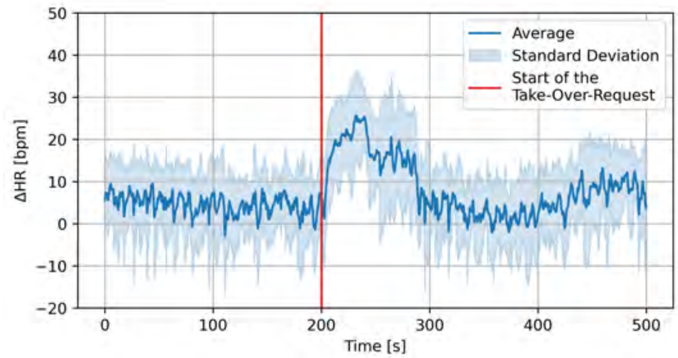

FIGURE 5: Relative change in the Heart Rate (ΔHR) during the simulation session (avg response ± std). The signals (*N*=6 participants) were aligned in time based on the start of the Take-Over-Request alarm. The HR increases in all subjects after the start of the alarm.

TABLE 3: Parameters measured on HR signals.

Domain	Parameter	Unit	Meaning
Time	MeanNN SDNN RMSSD	[ms] [ms] [ms]	Mean value of the Normal-to-Normal (NN) beats and variability in short and long term period
Frequency	Low Frequency band (LF) High Frequency band (HF) LF/HF ratio	[ms^2] [ms^2] [%]	Autonomic Nervous System oscillatory components
Non-linear	Sample Entropy Lempel-Ziv complexity	[1] [1]	Recurrent patterns and rate of new patterns in time

5. CONCLUSION

The aim of the research was to understand the human drivers' perception of L4 AVs during the take-over scenario. Preliminary tests have been crucial in highlighting simulation criticalities and validating the drivers' assessment process. A key aspect of the analysis was to merge qualitative and quantitative indicators. The first ones proved the realism of the simulation environment and a good perception of L4 AVs. The second ones had the objective of evaluating the physiological response and proving the correct definition of the take-over time. To this end, all participants could regain control of the vehicle within the time budget. Furthermore, relative changes in the heart rate signals, shown in Figure 5, provided a measure that could be used to separate different driving conditions. In the future, gathering data from a larger pool of subjects could allow to validate these preliminary results and to further investigate the ECG-derived HR signal. The project will expand by integrating other physiological signals, such as EEG, and EDA, possibly along with the forces applied to the steering wheel. These signals will be analyzed in order to obtain a personalized understanding of the underlying physiological response that the simulation generates in the subjects, leveraging also the use of machine learning models [42]. Moreover, computing parameters in time, frequency and non-linear domains, such as the ones reported in Table 3, could further help to investigate the drivers' status and the potential differences which the various driving conditions are able to generate in the physiological control systems [43–45].

ACKNOWLEDGMENTS

This research activity has been funded by EU – NextGenerationEU, M4C2 I1.1, Progetto PRIN 2022 "HL4IT", Prot. 2022L3M25K – CUP D53D23003750006.

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