Design Requirements for the Definition of Haptic Messages for Automated Driving Functionalities

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Keywords: Haptic and Tangible Devices, Automated Driving, Design and Evaluation.

Abstract: As the number of advanced driving assistance systems grows, there is an increasing number of interactions between the driver and the automated system of the vehicle. Requests to transfer control from the automated system to the driver, new information sources increasing driver workload, and safety-critical situations imply new challenges in the communication between the driver and the automated system. In this context, haptic feedback for steering-wheel control has proven to be a valuable strategy. This work aims to propose a novel description of the requirements needed for a driver-in-the-loop system capable of ensuring safety while providing haptic feedback to the driver. Furthermore, a set of haptic patterns for the steering wheel are proposed based on the described requirements, to be evaluated in future studies. As future steps of this study, a continuation of this study will be published focused on human centered factors of the driver.

1 INTRODUCTION

In recent years, a rising number of Advanced Driving Assistance Systems (ADAS) are being implemented in modern vehicles (Ziebinski et al., 2017). Current ADAS take operational functionalities from the driver such as longitudinal (Adaptive Cruise-Control or Emergency Collision Avoidance) and lateral control (Lane Keeping).

However, with the increase in the level of automation of vehicles as defined by SAE J3016, vehicle control systems take charge over more and more functionalities. Many works have suggested that reducing human intervention in automated vehicles will increase road safety (Lv et al., 2018), (Li et al., 2019) and (Morales-Alvarez et al., 2020). Hence, an important effort has been conducted by the automotive industry to develop functionalities with higher levels of automation.

In the transition to fully automated vehicles, the driver still has a fundamental role. When considering Automated Driving Levels (ADL), only ADL 4 and 5, conditional and high automation, completely remove the driver from the driving task. Functionalities with a medium or conditional level of automation (ADL 2 and 3) require the driver to supervise or partially control the vehicle (Marcano et al., 2020a). In these functionalities, the Takeover Request (TOR) plays a key role in the transition between the automated mode (controlled by the vehicle) and the manual mode (controlled by the driver) (Sasangohar and Cummings, 2010) (Mulder et al., 2008).

In this context, new challenges arise to ensure safe cooperation and interaction between the driver and the vehicle control systems, so that ADL changes such as TOR are properly executed by all agents. The driver-automated vehicle interface currently relies on approaches based on auditory or visual channels, such as Heads Up Displays (HUD), infotainment displays, and auditory alarms (Politis et al., 2015). However, these approaches can overstimulate the driver (Mehler et al., 2021), reducing their effectiveness for time-critical tasks (Strayer et al.,), such as TOR (Zhang et al., 2022).

As an alternative, haptic messages have been proposed, which use the actuators of the vehicle as feedback to the driver. Haptic messages can provide swift control transfer between the driver and the automated vehicle in cases such as TOR (Morales-Alvarez et al., 2020). Moreover, it has been demonstrated that haptic guidance considerably reduces the cognitive work-

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Sarabia, J., Diaz, S., Zubizarreta, A. and Perez, J.
Design Requirements for the Definition of Haptic Messages for Automated Driving Functionalities.
DOI: 10.5220/0011537700003323
In *Proceedings of the 6th International Conference on Computer-Human Interaction Research and Applications (CHIRA 2022)*, pages 171-178
ISBN: 978-989-758-609-5; ISSN: 2184-3244

load of the driver (Wang et al., 2018) (Shakeri et al., 2016), and that it improves handover transitions especially when applied together with visual feedback (Vito et al., 2020). A good illustration of this is the study conducted by the NHTSA (National Highway Traffic Safety Administration) where they compared different types of signals to alert drivers of a TOR. There, it was shown that the haptic feedback together with visual alerts generated reaction times with an average of 1.3 seconds, while only visual alerts took 4.8 seconds (Marinik et al., 2014). Regarding auditory cues, (Harrison et al., 2010) shows that they have a considerably short response time, especially when used together with visual feedback.

Looking for short response time channels, several authors have proposed works about situational awareness focused on retrieving the driver from the distracted to attentive in the fastest possible way. Auditory and haptic channels show the best time results (Ploch et al.,). However, while there is an abundance of to auditory cues, the haptic channel is rarely overloaded. This facilitates the haptic signals to be more rapidly perceived (Strayer et al., 2003). Furthermore, haptic perception appears to be resilient to high cognitive load conditions (Törnros and Bolling, 2005). However, this is still an open research area, as strategies to define the haptic messages, and the definition of these in terms of evaluation of their acceptability by users in real and simulated scenarios is still missing. In particular, note that when considering a medium level of automation, the driver is generally required to have at least one hand on the steering wheel. This additionally opens a gap for ADAS to be complemented with haptic feedback through the steering wheel.

About the type of equipment used for the haptic feedback, the current literature is mainly focused on small actuators installed on the steering wheel. However, there are fewer studies where the main steering actuator of the EPS (Electric Power Steering) is used. This is generally used to provide guidance (Beruscha et al., 2011), or used with low frequency profiles (Talamonti et al., 2017).

In the context of human machine interaction, the HADRIAN European Project has been proposed (had,). This project, funded by the EU Horizon 2020 program, aims at creating a novel interaction approach between the driver, the vehicle, and the road infrastructure. This interaction pretends to be adaptive towards the state of the driver and to the operational design domain, conveying an idea of fluid interaction with different HMIs (display, alarms, HUD, haptic feedback, etc.). In this sense, haptic devices are proposed as a tool to communicate with the driver regarding drive mode transitions, take-over requests, or message delivery. Hence, in this framework, two main contributions are proposed in this work: 1) a driving simulation framework, which ensures human-in-the-loop testing for haptic messages, as a tool to evaluate future works in this area; and 2) a set of design specifications for haptic messages using the steering wheel.

The rest of the work is structured as follows. Section II describes the equipment used to study the haptic feedback. Section III points out the requirements for safe use of the haptic feedback in steering wheels. Section IV proposes a methodology to design a set of haptic icons that fulfils the previous requirements. Section V shows the resultant haptic icons. Section VI offers a concluding overview of the obtained results and points to future works where user-centered studies validate the proposed icons.

2 DRIVING SIMULATOR FOR HAPTIC HMI TESTING

As stated in the introduction, there is a need to further test and evaluate approaches that consider the driver and automated vehicle interaction. In this work, a framework based on a driving simulator with a haptic steering wheel has been proposed, developed in the context of the HADRIAN project.

The proposed setup is detailed in Fig. 1, which is based on an off-the-shelf racing simulator, in which an Augury H kit haptic steering wheel has been integrated.

As seen in the Figure, the simulation setup includes three 32 inches LDC screens, a 120W stereo sound system, racing simulator pedals with mechanical damping, a fully equipped PC that runs the simulated vehicle and environment, a touch display to emulate secondary activities by the driver and a racing seat.

The simulation environment is based on Dynacar (Marcano et al., 2020b), developed by Tecnalia, which allows realistic vehicle dynamics modeling in real-time, including force feedback for the driver. Dynacar simulation framework includes a map editor and allows 3D representation of the vehicle in the selected scenario, so that it can be easily used as a driving simulation. A Mercedes Class E vehicle has been selected as the study case implemented in the setup (Marcano et al., 2020a). The inertia and damping of the steering system have been simulated based on the previously described case, then the actuator provides a more accurate response.

As previously detailed, the simulation setup has been complemented with the introduction of a haptic steering wheel, with the aim of testing and evaluating

Figure 1: Simulator setup.

vehicle-driver shared control approaches, and interaction strategies. The haptic wheel setup is composed of three elements: a wheel, a motor controller, and a motor.

The servomotor is a brushless DC motor in which a current sensor and an incremental encoder have been attached. The actuator is a MiGE model 130ST, which can exert a maximum torque of 18 Nm and provides 1.5 KW.

The racing steering wheel is a standard metal-core and leather-cover steering wheel used in common driving simulators. Thanks to its metallic core and it is tight fixation to the actuator, all vibrations are directly transmitted to the hands of the driver. The steering wheel includes a small Bluetooth 3.0 controller fixed at the right spoke, allowing it to be used with the right thumb. Its purpose is to change the driving mode from Automated to Manual modes (and vice versa).

Finally, the motor controller is composed of a Simucube motherboard, an IONI PROHC driver control unit with a maximum intensity of up to 25A, a safety emergency button and all the necessary interfaces to connect it to the simulator computer.

3 DESIGN REQUIREMENTS FOR THE DEVELOPMENT OF HAPTIC MESSAGES

The setup will be considered as the basis for developing and evaluating haptic messages for the driver. However, some requirements must be considered when defining haptic feedback signals for steering wheels.

The steering wheel is the lateral controller of the vehicle. Modifying its dynamics through vibrations can lead to potential control loss or deviations from the vehicle trajectory. Steering wheels can be coupled or uncoupled (Marcano et al., 2020a). If it is uncoupled (or drive-by-wire), there is no such constraint, as vibrations do not necessarily need to be transmitted to the movement of the wheels. If the steering is coupled, however, safety issues must be considered, among others.

From one side, haptic feedback should be felt in the hands of the driver but must not affect the trajectory of the vehicle. However, this goes against the nature of the working principle of the electric-driven steering wheel, as its movement is generated through its shaft. Hence, haptic signals must be centered around zero, so that the net movement produced by haptic vibrations is counterbalanced. This way, no lateral deviation from the trajectory will be caused by the haptic pattern.

From the other, haptic patterns in the steering wheel must be distinguishable from vibrations in the vehicle caused by road roughness. At the end of the day, the steering wheel is by itself an interface to feel the road. If haptic patterns may induce the driver to think that there was a bump in the road, or to believe that something happened to the tires, this could have a degrading effect on the perception of the road and, consequently, on vehicle control.

Regarding the functionality of the steering wheel, haptic patterns should not block or reduce the driver's control over it. When a haptic signal is activated by the system, the driver must be able to keep controlling the trajectory of the vehicle as if there was no such signal. Thus, the haptic pattern must not only be balanced around zero considering the entire pattern but also in small intervals of time, so that there is no torque applied in the steering wheel long enough to change its trajectory or to be excessive to be overridden by the driver.

In addition, regarding the durability of the system, the haptic patterns must not damage the mechanical components of the steering column. Vibrations are a widely studied field of mechanics and can lead to serious damage if they are not previously considered (Rouillard, 2014). When tuning the frequencies of the haptic patterns, natural frequencies of the system must be avoided. In this work, this is not the main focus, as a driving simulation environment is used. Future works require a study case when the proposed haptic patterns are brought to real vehicles.

4 DESIGN METHODOLOGY FOR HAPTIC MESSAGES

Based on the requirements analyzed in the previous section, in this one, the three main design strategies followed to design the set of haptic messages proposed in this work are defined.

4.1 Definition of Zero-centered Patterns

Regarding the zero-centered haptic patterns, in this work, two types of patterns are proposed. On the one side, oscillatory motion patterns. That is, haptic patterns composed of sine-based vibrations. And on the other side, short pulses that are felt like little strokes on the steering. The latter also have the same positive and negative component. This way, the total applied torque of the actuator will produce a null amount of work in both cases, generating no total displacement.

To achieve the desired haptic patterns, the actuator must be capable of reproducing the desired pattern properly. In addition, internal frictions and nonlinearities of the system may cause lateral displacements. To evaluate these effects, the following experiments have been performed.

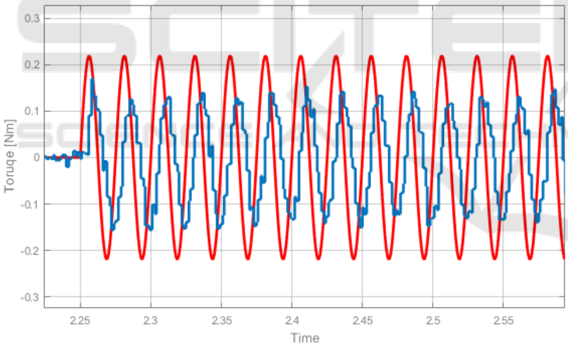

Figure 2: Torque response of the 1.5 s vibration (red-reference /blue-response).

First, the response obtained when sending a torque sine input in the steering wheel has been analyzed. Fig. 2 shows the torque reference input in red and the measured torque output in blue. Even if the measured signal is slightly discretized, and there is a phase shift, it can be observed that the response of the actuator is capable of following the set input in terms of frequency. Note that the main focus in this section is the haptic feeling provided by the system. In addition, this figure shows the worst-case scenario, this is, the response of the motor to the highest frequency at the reference, which sets the maximum frequency of the system (considering the simulated inertia and damping are part of the measured net torque) at 40 Hz. Regarding the amplitude, a higher value does not provide a difference in the output, as the torque output of the actuator has a gradient saturation, meaning that for such frequency, this is the highest value it will reach.

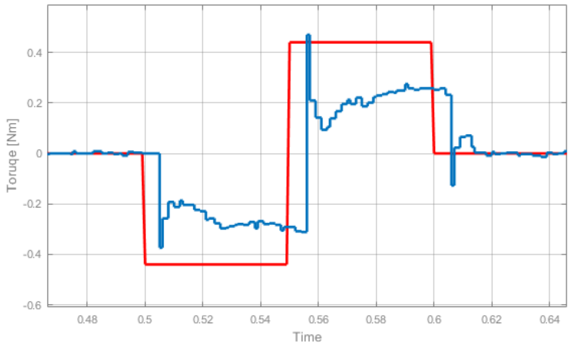

Figure 3: Torque response of the pulse signal.

Second, pulse responses have been tested, as shown in Figure 3. Similar to the previous case, the haptic feeling of the reference can be executed by the motor, as transitions (peak values), and then a constant torque area, can be defined. Note that apart from the reference torque sent, there are also the components of the simulated damping and the inertia, which are responsible for the transitory effects.

Hence, the aforementioned patterns (sine and pulse) are appropriate to develop haptic messages in the proposed setup.

4.2 Definition of Easily Distinguishable Patterns

If vehicle vibrations and haptic patterns are considered, as previously stated, those two sources of information must be distinguishable. Unfortunately, road vibrations may not have a regular pattern, as sporadic bumps or road roughness changes can cause unexpected vibrations in the vehicle. However, most common vibrations in vehicles are caused by the interaction between the roughness of the road and the surface of the tires.

Road roughness may be described as the elevation profile obtained along the wheel tracks over which vehicles pass. Such profiles fit the general category of broad-band random signals. When passed by a vehicle, its velocity determines the frequency at which such profile will be collided, generating vibrations on the wheels of the vehicle. Some studies (Rouillard, 2014) suggest that for a velocity range between 20 and 100 km/h, the predominant road vibration is between 1 and 10 Hz. But this is the vibration generated in the floor of the vehicle, after being filtered by the damping of the vehicle. However, as (Agostinacchio et al., 2013) shows, the vibrations generated by the road roughness at driving speeds between 25 to 100 km/h, go up to 100 Hz and higher. And those are the ones that are felt in the steering wheel in coupled steering columns, as the system is in direct contact with the vehicle tires. Indeed, this is easily demonstrable just by taking a sound system and reproducing signals increasingly between 30 and 200 Hz. The obtained sound is equivalent to that heard while driving a car.

In (Gillespie and Sayers, 1981), a study was performed evaluating frequencies between 0 and 200 Hz. There, it is shown that a frequency variation to be haptically perceivable requires intervals of at least 10 Hz. Thus, a couple of conclusions can be obtained from here: first, having a 40 Hz upper limit established by the actuator, there are few frequencies left to design the haptic feedback patterns. And second, the haptic feedback will be in the range of the typical vibrations found in the vehicle steering.

For that reason, the approach to obtain some distinguishable haptic patterns will not be focused on specific frequency ranges. Instead, 3 other variables will need to be prioritized: first, the regularity of the signal; second, the duration; and third, its amplitude. As road vibrations have chaotic components, regular structured signals may provide a more trustworthy feeling of their presence. Regarding the duration and the amplitude, a balance between what is perceivable and what is uncomfortable will need to be obtained.

4.3 Definition of Patterns to Reduce the Effect on the Steering Wheel

As previously detailed, the applied haptic patterns must not affect the drive. However, it could be considered that applying specific torques in the steering column could derive in deviations of the vehicle trajectory and possible control lost. To check whether the proposed haptic patterns could really affect the safety of the drive, the following tests have been conducted.

First, a sequence of equal sine waves (0.4 Nm of amplitude, 40 Hz of frequency and 1.5 s of duration) has been sent as input to the system repeatedly during 300 s. The aim was to evaluate the angular displacement generated on the steering wheel. Results are shown in Fig 4.

Each of the repeated patterns zoomed in Figure 4 are equal to the ones presented in Figure 2. The aim of Figure 4 is to show the total deviation of the steering wheel after applying the haptic icon a repeated number of times (133 times in this case). After the test, the total deviation of the steering wheel shown in the second graph of the layout is less than 1º.

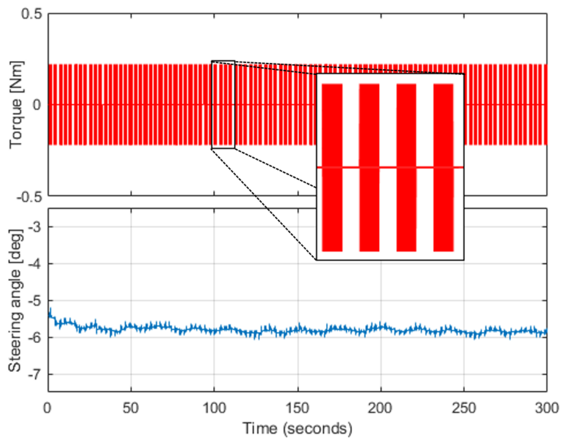

Figure 4: Sequence of sine patterns and angular deviation of the steering angle.

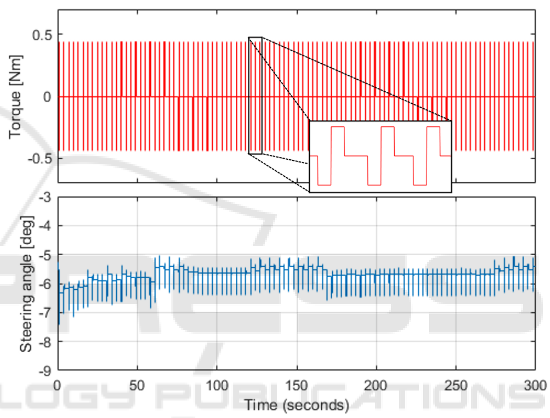

Figure 5: Sequence of pulse patterns and the angular deviation of the steering wheel.

This same test has also been conducted for the other haptic pattern proposed, for the pulse (Figure 5). Results show, with the same amount of repetitions, an overall deviation of up to 2º. However, the instantaneous deviation of the steering angle is much higher for the pulse than for the sine-based vibration. This is because the amplitude achieved in the pulse is higher than in the first pattern, and the pulses are longer in time. To obtain a feeling about how potentially dangerous these deviations could be, a theoretical and a practical approach is proposed.

From the theoretical perspective, the effect of the steering wheel on vehicle orientation can be calculated by a model, such as the bicycle model formula. This is a stationary approximation, without considering the transitory damping effects of the tires that could happen during the haptic pattern duration. The equation goes as follows,

$$\beta = \mathrm{arctg}(l_r \tan(\delta)/L) \quad (1)$$

where β is the slip angle, l_r the distance between the center of gravity of the vehicle to the rear axle, L the distance between the rear and front axles, and δ the front wheels angle. As δ is proportional to the steering wheel angle, it can be directly related the slip angle with the steering wheel angle. The typical ratio between δ and the steering wheel angle tends to be around 15:1, meaning that a turn of 15° in the steering wheel implies 1° in the tires.

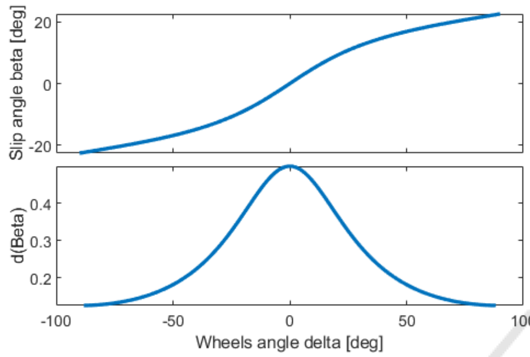

Figure 6: Graphic representation of the bicycle model formula and its derivative.

Figure 6 shows the graphic representation of the bicycle model. The maximum variation of the slip angle is at the maximum point of its derivative, that is, when δ is closer to zero. Thus, computing the calculation of the obtained 2° deviation for the pulse pattern, a slip angle of 0.0667° is obtained. This implies that, for instance, driving at a speed of 90 km/h (25m/s), an instantaneous deviation caused by the haptic pulse would deviate the trajectory of the vehicle 0.03m after one second. This is considering no damping of the system nor the driver hands.

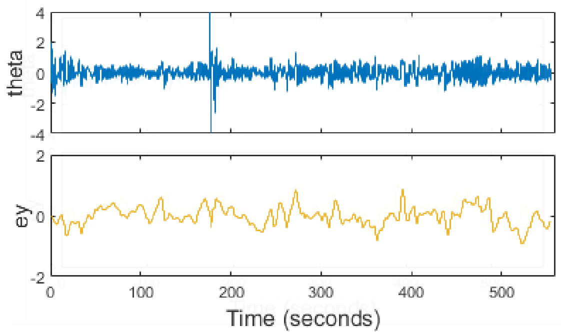

Figure 7: Steering wheel angle and lateral error recorded during a 560 s drive in a straight line in the simulator.

From an experimental perspective, a 10-minute ride has been tested in the simulator on a straight-line highway to measure the periodic fluctuation of a driver. As it can be seen in Figure 7, except for an outlier in second 190, the rest of the drive is within a range between -2 and 2 degrees. In the lower subplot, the lateral deviation (in meters) is shown for the lane center. Considering the mean frequency of the driver making corrections, it is calculated that every 0.895 s a lateral correction cycle is performed. In other words, the lateral oscillation of the driver is approximately around 1 Hz.

This implies that the maximum lateral deviation caused by the haptic pattern would be inside the range of a deviation of a generic ride. Thus, as long as the driver has the hands on the steering wheel, the effect on the drive is negligible.

Based on the aforementioned design strategies, the following set of haptic messages have been proposed for three main approaches: message notification, take-over requests (TOR) and hand-over transitions (Figure 8).

Message notification patterns are designed as short, and mainly composed of pulses. They are intended to provide quick, non-intrusive and non-critical messages to the driver. That is, they are supposed not to be urgent, but to catch the attention of the driver easily.

TOR patterns are mainly composed of long vibrations, whose amplitude increases in steps as the urgency to take over the control increases. They are all 40 Hz in frequency and mainly last about 5 seconds. They are supposed to increase the level of urgency during the time, providing a countdown feeling.

Finally, the hand-over transition patterns are designed in two different ways. The first four approaches are designed looking for a continuous increase or decrease of the amplitude, while the resting four have a continuous change in frequency. This duality has been proposed to prove that amplitude-based transitions are more reliable than frequency-based transitions, as frequency jumps are less noticeable. Their design aim is that the driver receives a transition feeling, as if something was switching on and off.

This haptic set is defined so that the actuator system proposed in the driving simulation environment can reproduce the required vibrations to the driver. However, note although the haptic steering wheel can follow the defined haptic messages, user-centered studies will be required to evaluate the acceptance and effectiveness of the messages.

5 CONCLUSIONS AND FUTURE WORKS

Haptic feedback on the steering wheel will be highly beneficial in future ADAS, as there is a strong need

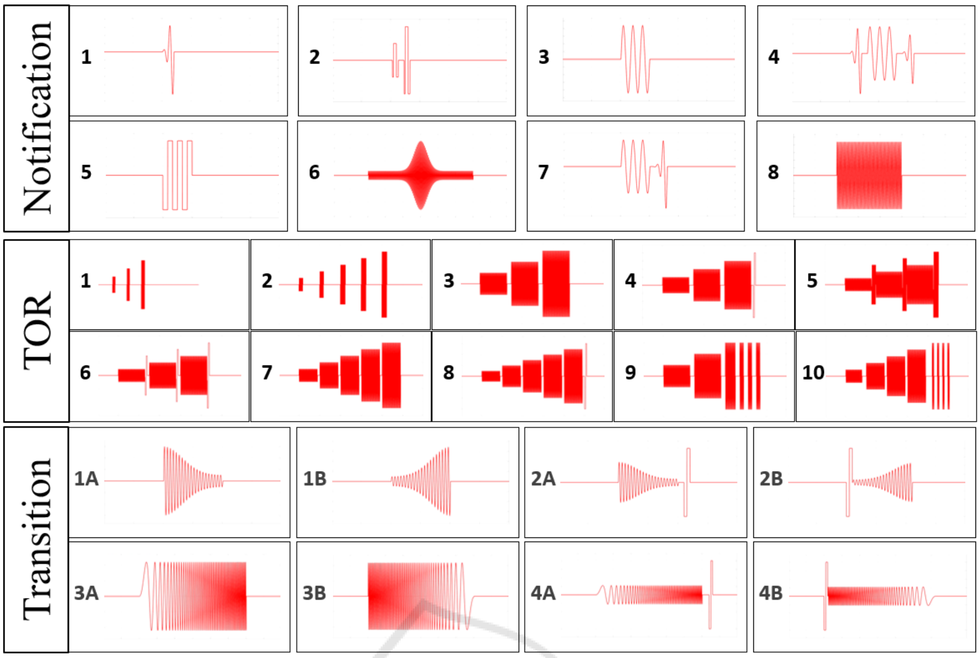

Figure 8: 1 to 8 icons: Message notification icons. 1 to 10 icons: Take-Over Request icons. 1A to 4B icons, hand-over transition icons.

for safe critical interfaces that ensure rapid intervention from the driver. Besides, haptic feedback will not imply a safety issue regarding vehicle control, even in the edgiest situations. Indeed, it will increase safety by improving the interaction between the driver and the vehicle and reducing driver workload. The main contribution of this work is a new HMI concept, based on a set of haptic messages for ADS, together with the defined requirements for the implementation of safe haptic messages.

The simulator shows how an off-the-shelf racing steering wheel can work as a haptic feedback interface, as it fulfills all the previously defined requirements. Some interactions with the haptic messages show their potential for ADS specific cases. Nevertheless, user-centered tests will be needed to evaluate and improve the proposed set of haptic patterns.

ACKNOWLEDGMENTS

This work is supported by the EU Commission HADRIAN project and the Government of the Basque Country by means of AUTOEV@L project (KK-2021/00123). HADRIAN has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 875597. This document reflects only the author's view, the Innovation and Networks Executive Agency (INEA) is not responsible for any use that may be made of the information it contains.

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