www.cad-journal.net Computer-Aided Design and Applications™

# A Study on Haptic Actuators to Improve the User Experience of Automotive Touchscreen Interfaces

Andrea Picardi[1], Giorgia Ballabio[2], Venanzio Arquilla[3] and Giandomenico Caruso[4]

[1]Politecnico di Milano, andre.picardi@polimi.it
[2] Politecnico di Milano, giorgia.ballabio@polimi.it
[3] Politecnico di Milano, venanzio.arquilla@polimi.it
[4]Politecnico di Milano, giandomenico.caruso@polimi.it

Corresponding author: Giandomenico Caruso, giandomenico.caruso@polimi.it

**Abstract.** This paper presents a novel analysis of haptic actuators for touchscreen interfaces within the automotive industry. The research, distinct from existing studies, aims to identify the most suitable actuators for delivering effective and efficient haptic feedback, focusing on practical implications. Six experts reviewed three haptic effects and four actuators, providing qualitative feedback on force, quality, reactivity, and duration using a 7-point Likert scale. The test was conducted in a car-simulated environment with a car seat and a central touchscreen display. The four actuators were positioned behind the touchscreen display, each connected to separate control modules communicating via serial interface with the computer managing the Graphic User Interface. This research provides practical insights into choosing haptic actuators for automotive touchscreen interfaces, focusing on enhancing user experience and feedback. The findings can be directly applied to enhance car haptic feedback systems, improving safety, user engagement, and driving experiences.

**Keywords:** Haptic Feedback, Automotive, Human-Machine Interface
**DOI:** https://doi.org/10.14733/cadaps.2025.136-149

## 1 INTRODUCTION

Touchscreen technologies are almost a standard in automotive to control in-vehicle infotainment systems. The main reason why this interaction model is considered successful lies in enabling multifunctional systems. The ever-increasing number of features makes a direct mapping between functions and control commands unviable. Consequently, integrating digital on-screen interfaces becomes necessary [7]. The direct intervention of the user on the screen to control its functions is only one of the possible interaction patterns. Kern and Pfleging describe three different interaction models with those systems: context-dependent controls, external controls, and touchscreens [18]. Context-dependent controls, with their physical quality, suggest the appropriate interaction, and they are buttons, knobs, and leverages. External controls need a screen to finalise the interaction, and they are, for example, the touchpads. With a touchscreen, input and output are co-localized, and the interaction can be considered more direct.

Adopting this technology in the automotive realm took longer than in other application fields. The first example was the 1986 Buick Rivera, with its Graphic Control Centre (GCC) [34], which was quite advanced and sophisticated. This technology was expensive then, but it represented an excellent opportunity for the manufacturer to make the experience more interactive. However, introducing this new interaction modality immediately opened a critical issue, which still needs to be solved. Interacting with a touchscreen reduces visual attention on the road, and it determines driver distraction, significantly affecting safety and driving performance [30]. Indeed, in 1990, Buick removed the GCC because drivers needed to take their visual attention off the road for every simple action, like changing the temperature or switching the radio [17]. The motivation for visual distraction is that touchscreen technology uses visual feedback as interaction [27]. Moreover, users must visually seek on-screen commands because of the lack of tactile and kinaesthetic feedback [7]. These limitations become particularly critical when the context of the use of these interfaces relates to safety systems [15]. Context of use is one of the factors that determines usability in general. In the driving scenario, interactions with IVIS (In-Vehicle Infotainment System) occur in a dual-task environment where any activity happens while driving. The goal of interface design always remains to facilitate the driving activity by reducing the interference from other activities and distractions. For this reason, the efficiency of interaction in driving conditions is assessed by comparing the time spent on primary tasks with the time spent on secondary tasks.

Introducing haptic feedback on touchscreens can reduce visual attention requests during interaction, and multimodal interaction, including visual, audio, and haptic feedback, is preferred by users [3, 26, 27]. Although specific modes are more effective than others at reducing visual driving distractions, it is beneficial to employ multi-modal systems to complement each other's limitations [22]. For instance, voice-based interactions enable the driver to avoid using the touchscreen and maintain the focus on the road. Nevertheless, this modality introduces challenges due to its sequential and temporal nature, which can increase the reliance on short-term memory [4]. Consequently, this shift in cognitive load may lead to distractions that are not visual but cognitive.

Haptic feedback is already used in other car parts related to driving activity, such as the steering wheel, seat belt, pedals, seat, dashboard, and clothes [12]. Unlike the cases mentioned above, the contact between the user and the touchpoint is not constant when interacting with a touchscreen display. Still, it occurs only when the user interacts with the display. For this reason, haptic feedback on a touchscreen is more informative than a warning, giving information on system status and confirmation of some action performed by the user, which affects the moment of evaluation more than the moment of execution.

According to Norman, the gulf of execution describes the moment users try to figure out what they can do and how a system operates [23]. The gulf of evaluation identifies feedback and conceptual models that allow the user to understand what happened. When introduced in touchscreens, haptic feedback is usually limited to confirmation of an action; it occurs once the target has been located on the screen [5]. Hence, haptic feedback has an impact on reducing second glares after the input [27]. Research is also investigating how haptic feedback can be effectively used in the first phase of exploration [31,8]. However, the role of haptic feedback, especially if integrated with other feedback, in enhancing safety by reducing visual attention requests to perform secondary or tertiary tasks is lacking in studies on how to shape and optimise the input [5].

This research describes selecting and evaluating actuators that provide different force feedback sensations. This investigation focuses on the vibrotactile method, which delivers direct vibration between the screen and the finger. The goal is to explore the user perception of haptic feedback for vehicle touch screens. This exploration aims to reduce the visual attention required for interaction. The study is based on the importance of haptic feedback, as supported by previous research. It serves as a preliminary investigation for future, more in-depth studies. The research was conducted empirically by developing a support system for testing various actuators.

The paper is structured as follows: Section 2 discusses related works and research. Section 3 describes the methodology, including the selection of actuators and the test setup and procedure. Section 4 presents the test results and their discussion. Finally, Section 5 concludes and outlines thoughts for future developments.

## 2 RELATED WORKS

Surface haptics is a broad area of research that could find many applications, such as programming haptic effects on physical surfaces such as touchscreens. In this field, "machine haptics" identifies technologies able to recreate tactile stimuli. A detailed review that classifies technologies based on the direction of stimulation is provided in [2], and the authors highlighted that the force feedback can be modulated in either the normal or tangential direction. The review covers the three most popular actuation methods: vibrotactile, electrostatic, and ultrasonic. Research on different touchscreen actuators typically identifies electromagnetic options, such as Eccentric Rotating Mass (ERM) and Linear Resonant Actuator (LRA), as the preferred choice due to their affordability, simplified design, and low power consumption. [24]. However, these technologies have limitations in providing complex tactile sensations. In [10], the authors reviewed various studies proposing solutions for the haptic enhancement of touchscreens based on the type of actuation they involve. They concluded that the trade-off between expressiveness and usability remains difficult despite research efforts to develop haptic hardware.

Several studies have assessed the influence of haptic feedback on interacting with touchscreens while driving. In [26] the authors evaluated through a survey conducted on a driving simulator that haptic feedback integrated with visual feedback helps compensate for the increased mental workload, primarily when visual feedback is restricted. Subsequently, the study was extended by investigating the contribution of haptic feedback under different conditions of visual feedback latency. The results show that, with haptic feedback, there is a decrease in second glances even under conditions of visual feedback latency [27]. These results are further validated in [3]. The authors demonstrate that haptic feedback significantly reduces eyes-off-road time and perceived workload. They also noted that human distraction cannot be entirely avoided when using touchscreens due to the need to seek input visually.

Other studies explored using touchscreens to assist users in identifying Graphical User Interface (GUI) elements rather than solely relying on them for confirmation, as already reported in [31], where the authors describe the HapTouch system. This system is a force-sensitive touchscreen device with tactile feedback generated through a linear actuator. This system supports the exploration of discriminating different pressure levels. Results of the pretest show a significant reduction in error rate, especially during input tasks. The HapTouch system referred to the 0-2 state model proposed in [7] to describe direct input devices as touchscreens. State 0 means no interaction, state 1 indicates the system tracking the movement, and state 2 indicates when the actual interaction occurs. In the interaction with the touchscreen, state 1 is bypassed. Coe et al. propose a method to implement a universal volumetric haptic actuation platform in a recent study [9]. Results of the experimentations with this platform show that volumetric feedback could improve the performance of detecting specific elements on the interface. Subjective comments demonstrate the user's ability to recognise the 3D features of GUI.

Other studies consider integrating this type of feedback as an additional modality in addition to visual and auditory feedback. In a research conducted in 2008, Lee and Spencer compared unimodal (visual) feedback with various kinds of multimodal (bimodal and trimodal) feedback [20]. Results from objective and subjective measures clearly show that the presentation of trimodal feedback enhanced driver performance. Burke et al. reached a similar conclusion after a meta-analysis of 43 studies: visual-tactile feedback provided advantages in reducing reaction times and improving performance scores. Still, it was not effective in reducing error rates [6]. Pitts et al., in a study conducted with 48 respondents, reported that a preference was expressed for multimodal feedback over visual feedback alone [27]. The design of these different feedback modes must be integrated to ensure that users have a holistic and coherent experience. Tomotaka Igarashi, the engineer in charge of Ariya's interior Human-Machine Interface (HMI)development for Nissan, describes the design process for the haptic feedback and highlights how sound and haptic are inseparable [33].

The exploration of haptic feedback in user interfaces encompasses various dimensions, including examining users' affective responses and the design intricacies of specific tactons. The affective response indicates the general psychological individual state, including emotions and mood [14]. For example, Pitts et al. conducted a preliminary study before a specific test to identify one haptic feedback effect to use in the main trial [25]. This experimentation used a Touchsense unit with pre-fitted haptic feedback actuators and control hardware. All users were required to operate the screen with their left hand as per an in-car scenario (right-hand drive). Furthermore, users wore ear defenders during the evaluation to reduce the cross-modal influence from the audible output of the haptic touchscreen actuators. Through an interface, the user had the opportunity to test and compare different effects belonging to five groups: "Pulse Click", "Crisp Click", "Smooth Click", "Double Click", and "Complex". Results show a preference for the "Crisp Click," used in the main study. Weng and Yu, in original research on the 2013 Cadillac XTS, the first commercial implementation of touchscreen haptic feedback, found that users reported feeling more confident and satisfied when using an interface with haptic feedback compared to a non-haptic tablet [35]. In a comprehensive study, Gaspar highlights the necessity of designing actions for touchscreen interactions that are quickly recognisable by users [13]. Breitschaft et al. create a framework for the design of haptic processing in automotive user interaction [5]. They identified some guidelines for the design of the feedback according to different phases. For example, it should be evident in the detection phase and intuitive in the identification phase. The perceived quality of the feedback depends not only on the functional evaluation and personal preferences but also on the latency and timing. Schneider et al. highlight how it should be fast and synchronised with other modalities [32].

However, detailed guidance on effectively implementing haptic feedback for touchscreen interfaces still needs to be improved. Addressing this gap is essential for advancing the usability and adoption of haptic feedback technologies, particularly in critical environments such as automotive interfaces, where user safety and experience are crucial.

## 3 METHODOLOGY

This section outlines the systematic approach to investigate various aspects of haptic effects, actuator selection, test setup, and testing procedures. Firstly, the definition of haptic effects is crucial as it provides the basis for understanding the tactile sensations that need replicating on physical surfaces, particularly touchscreens. Next, selecting appropriate actuators is discussed, considering factors such as affordability, power consumption, and the ability to provide the desired tactile feedback. The test setup details the environment and equipment used to evaluate haptic effects, ensuring consistency and accuracy of measurements. It also outlines the test procedure, explaining how participants interact with the system and provide feedback, thereby validating the effectiveness and usability of the selected haptic effects and actuators.

### 3.1 Definition of Haptic Effects

To explore the integration of haptic feedback within automotive touchscreen interfaces, we started identifying the vibration parameters and the formulation of haptic effects; in this phase, we have been influenced by both technical considerations and design principles established by industry leaders, including Google [21] and Apple [28]. This decision aligns our feedback designs with existing guidelines and serves a dual purpose. Firstly, these guidelines are extensively employed and recognised in consumer products outside the automotive domain. Secondly, their widespread adoption fosters an expectation among end-users already accustomed to their presence.

By grounding our research in established principles while adapting them to the automotive context, we strive to enhance user experience and interface intuitiveness within automotive touchscreen interfaces. From this foundation, we identified two components that constitute the behaviour of the developed haptic effect: max amplitude and duration. At time $T_0$, the amplitude of the actuator vibration is set at a specific percentage of the maximum permissible value. Then, the amplitude linearly decreases until time $T_1$ (duration), as shown in Figure 1.

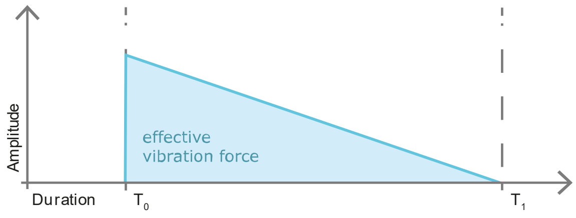


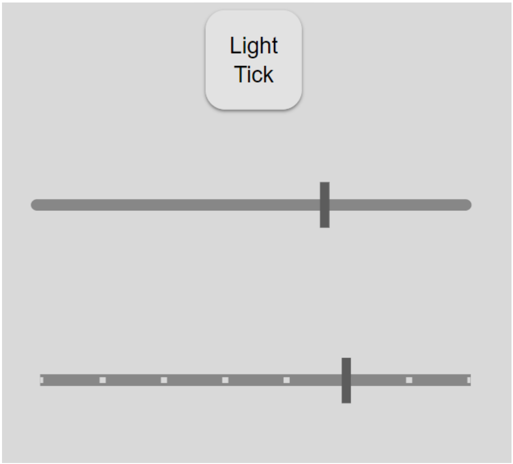

**Figure 1**: Haptic effect rendering.

According to this haptic rendering, we distinguished four distinct effects: Light Tick (LT), Medium Click (MC), Strong Click (SM), and Ramp Vibration (RV). Each effect has a different duration and max amplitude combination, as shown in Table 1.

| *Effect type* | *Duration* | *Max amplitude* |
|---:|:---:|:---:|
| Light Tick | 80ms | 33% |
| Medium Click | 120ms | 67% |
| Strong Click | 120ms | 100% |
| Ramp Vib. | 200ms | 33% |

**Table 1**: Haptics effects used for the test.

These effects were applied to touchscreen interactions, such as buttons, free sliders, and stepped sliders, independently or in conjunction, as illustrated in Figure 2. By incorporating a variety of interactions, we aimed to evaluate the adaptability and efficacy of each haptic effect across the spectrum of user interfaces commonly encountered in automotive HMI systems.




Button
- only one effect on press

Free slider
- medium click on press
- ramp vibration when the handle hits the borders

Stepped slider
- medium click on press
- light tick on steps when dragging the handle
- ramp vibration when the handle hits the borders

**Figure 2**: Types of interfaces and haptic effects evaluated during the test.

### 3.2 Actuator Selection

We have identified and assessed four types of actuators with different characteristics, as shown in Table 2. Three were LRAs, and one was an ERM. The selection process was guided by considerations such as compact design, availability, and prevalence in the field to understand each type's strengths and weaknesses comprehensively.

| *Test abbreviation* | *LRA-1* | *LRA-2* | *LRA-3* | *ERM* |
|---|---|---|---|---|
| Actuator type | LRA Z-Axis | LRA Z-Axis | LRA X-Axis | ERM - Coin Vibration Motor (BRUSH) |
| Dimensions L x W x H (mm) | 10 x 10 x 4 | 10 x 10 x 4 | 32 x 15 x 8 | 12 x 12 x 3.4 |
| Rated Voltage (V) | 2.5 | 2.5 | 2.0 | 3.0 |
| Operating Voltage (V) | 0.1 ~ 2.5 | 0.1 ~ 2.5 | 1.5 ~ 2.3 | 2.7 ~ 3.3 |
| Rated Current MAX (mA) | 170 | 350 | 300 | 80 |
| Typical Current (mA): | 145 | 317 | 270 | 48 |
| Rise Time MAX* (ms) | 10 | 10 | 50 | 90 |
| Fall Time MAX* (ms) | 50 | 40 | 120 | 50 |
| Resonant Frequency (Hz) | 170 | 170 | 100 | - |
| Rated Speed (rpm) | - | - | - | 9000 |
| Vibration Force (Grms) | 2.00 | 2.75 | 5.00 | 2.00 |

**Table 2**: Tested actuator characteristics (*at 50% of Maximum G force).

The first three types analysed are LRA actuators that function on the principle of resonance. They consist of a mass connected to a spring, forming a vibrating system. Applying an electrical signal at the resonant frequency induces vibration in the mass, thereby producing the desired haptic feedback. LRAs are characterised by their rapid response time, rendering them suitable for delivering precise haptic effects and thus providing nuanced HMI feedback.

Conversely, ERM actuators operate through the eccentric rotation of a mass. An unbalanced mass is attached to a motor, which spins rapidly, transmitting vibrations to the device. ERMs are known for their construction simplicity and compact design, making them cost-effective and easy to integrate. However, they are constrained regarding the frequency range they can generate and exhibit limited precision in controlling vibration intensity and pattern. This limitation poses challenges in applications requiring finely tuned vibrations, such as the context of our study. Despite their drawbacks, ERMs serve as a valuable point of comparison against LRAs.

Two LRA actuators (LRA-1 and LRA-2) had an oscillating mass on the Z-axis, normal to the touchscreen's surface, and one (LRA-3) on the X-axis, as shown in Figure 3. These three actuators also have increasing vibration forces and require different current inputs. The ERM actuator, instead, had a similar vibration force to the LRA-1 but considerably lower actuation current than the LRAs.

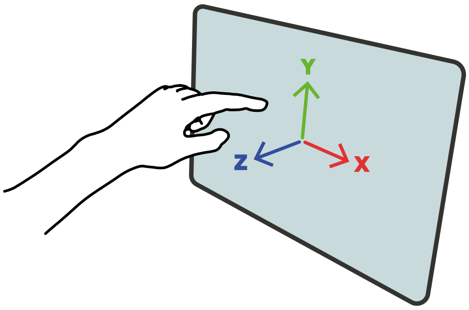



**Figure 3**: Direction of the axes on the touchscreen.

### 3.3 Testing Setup

To thoroughly evaluate the effects of haptic feedback, a review with six experts was performed on a static car simulator to test the drivers' user experience within the vehicle environment. Experts were selected based on their experience in design, engineering, and marketing fields in the automotive industry, specifically in the HMI field, thus allowing us to address the strengths and weaknesses of the evaluated system. This simulator replicates a car's interior's essential components, facilitating realistic user experience assessments. Featuring two car seats, a steering wheel, and a central touchscreen display, this setup aimed to emulate the interaction with an actual vehicle's human-machine interface, ensuring a more authentic testing environment.

The central touchscreen was a 16” LCD, with a resolution of 1920x1080 running at 60Hz with a 179° angle of vision. It weighed 2.24 kg, totalling 15 x 7 x 1 cm; a VESA mount was attached to the simulator structure. The display served as the primary interface for evaluating haptic feedback; participants engaged with various digital interface elements such as buttons, sliders, and stepped sliders through this display. The hardware setup of the testing bench comprised four actuators attached to the central touchscreen display. Each actuator was controlled by a haptic motor driver board (the Sparkfun DRV2605L [11]) and an Arduino Nano 33 IoT board [1]. This hardware configuration was linked via a serial interface to ProtoPie software [29], running on a computer connected to the central touchscreen, as shown in Figure 4.

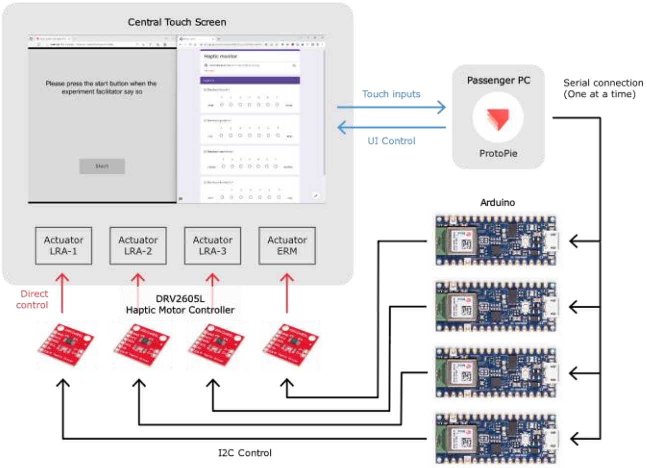



**Figure 4**: Hardware and software setup.

The Arduino boards controlled the actuators through the haptic motor driver board, ensuring the connection between the computer where the input interface was connected and the actuators. Instead, the haptic motor driver board directly controlled the vibrations, guaranteeing the proper actuation feedback thanks to the fine control that this controller allows for each actuator type. These parameters were selected before the test to ensure the proper actuator response for each type.

ProtoPie managed all touch interactions performed by users on the touchscreen, including the corresponding effects for each interaction and the display of the graphical user interface (GUI). It also communicated these interactions to the Arduino board. The GUI was divided into two parts: a clean interface containing the interaction elements (such as buttons and sliders), the text with instructions for the subject on the left part of the screen, and the web form on the right, as shown in Figure 5.

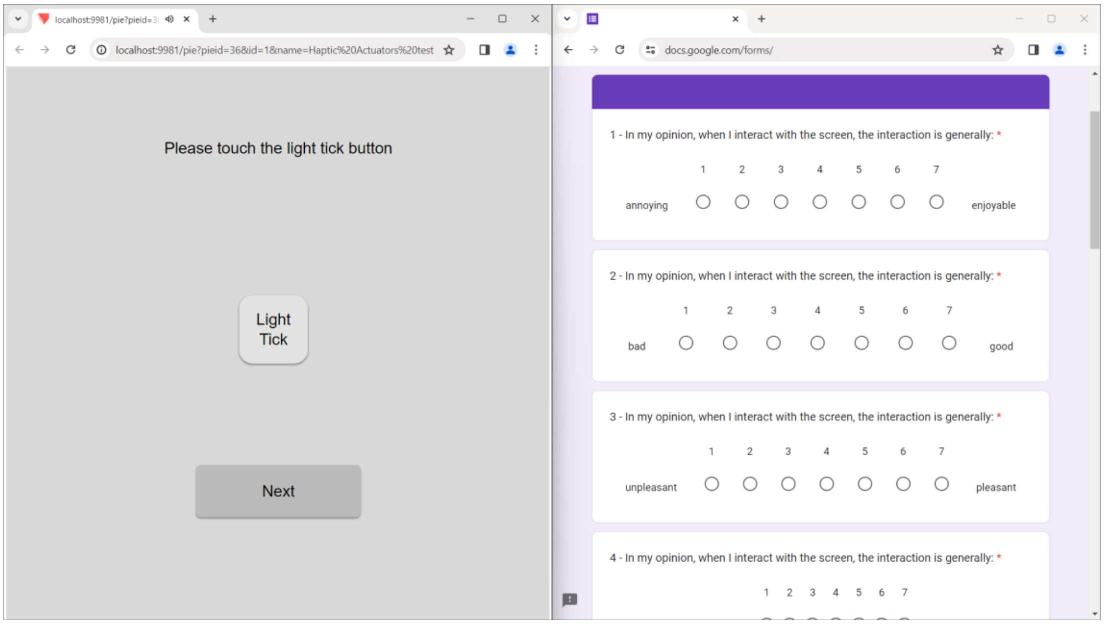



**Figure 5**: The graphical user interface used during the test to render the haptic effects (left) and the web form to collect participants' answers (right).

The testing bench setup and components were chosen to enable rapid prototyping. This platform provides a flexible and efficient means of testing and improving haptic feedback and evaluating user experiences in a controlled environment. By using these tools, we were able to quickly integrate and iterate touchscreen interactions and effects, making it easy to modify vibration parameters and conduct rapid and iterative testing before the final assessment.

## 3.4 Test Procedure

During the test, the experts were instructed to assume the driving position behind the driving simulator, grasp the steering wheel, and imagine themselves in a driving scenario. They were then invited to think aloud, providing verbal feedback on each perceived effect they experienced. Then, they were directed to interact with a single GUI element on the left part of the screen, as shown in Figure 6; this interaction lasted for thirty seconds, after which the participants were asked to complete a survey displayed on the right side of the touchscreen. The assessed GUI element was always available on the left side, ensuring that participants could continue testing the haptic feedback even while completing the survey.

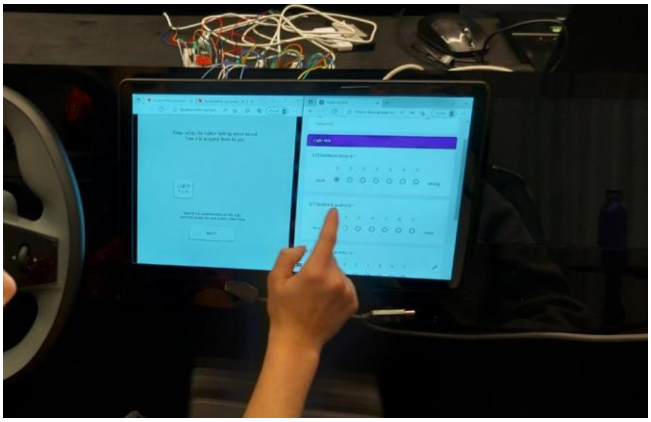


**Figure 6**: User during the evaluation phase.

The next one, related to the addressed GUI element, was presented after the subject completed the survey. The GUI elements were always presented one by one following this order for all the subjects:

- A button with a light tick;
- A button with a medium click;
- A button with a strong click;
- A slider (with medium click and ramp vibration);
- A stepped slider (with a light tick, medium click, and ramp vibration).

After the participants individually experienced each haptic effect in order, they tested all effects on a simplified GUI; in this phase, only the users' verbal comments were recorded. After each testing session, participants were given a one-minute relaxation period before evaluating the next haptic actuator. Following the same procedure, the order of the investigated actuators changed for each subject.

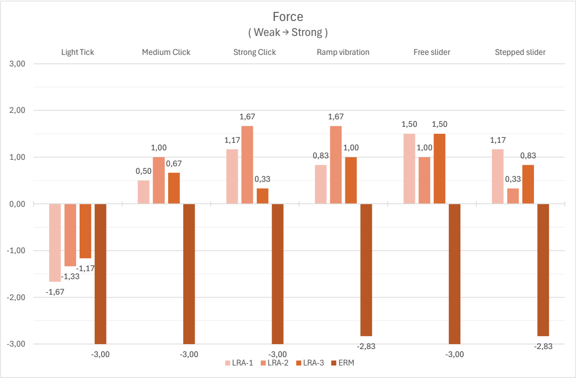
To minimise potential distractions, passive noise-cancellation headphones were provided to isolate participants from external audio noise generated by the actuators. This ensured that participants could focus solely on the evaluated haptic feedback.

Participants provided qualitative feedback using a 7-point Likert scale on four parameters: Force (Weak - Strong), Quality (Dirty - Clean), Reactivity (Delayed – Real-time), and Duration (Short - Long). These parameters were derived from the User Experience Questionnaire (UEQ) by Hinderks et al. [19]. Additionally, participants were encouraged to provide qualitative comments using the thinking-aloud procedure, allowing for a more nuanced exploration of their experiences. These open-ended comments were audio-recorded for further analysis, enabling participants to articulate preferences, perceptions, and any specific observations not fully captured by the survey.

## 4 RESULTS AND DISCUSSION

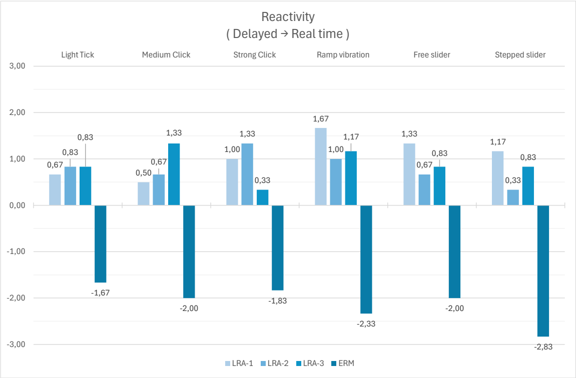
### 4.1 Test Results

After conducting the test with six experts, several key insights emerged regarding the perceived effectiveness of different haptic effects applied to automotive touchscreen interfaces. The evaluation of the force parameter indicated that the force perceived by users was notably low for the ERM actuator, as seen in Figure 7 (a); on the other hand, the perception of force for the LRAs actuators exhibited mixed results. For the light tick, they all performed similarly, and only by increasing the amplitude can we start to see the LRA-2 being perceived as stronger, as expected by its characteristics. Conversely, when evaluating the free and stepped slider, the LRA-2 was perceived as weaker than the other two LRAs. However, the low perception of force for the ERM actuator was unexpected; we think this was because one ERM actuator is too weak for a screen with this surface.

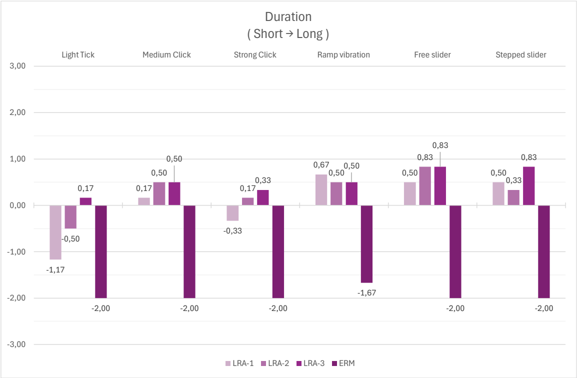



(a)


(b)




(c)




(d)

**Figure 7**: Graphs displaying the results of the survey categorised by the aspects being investigated: (a) Force, (b) Quality, (c) Reactivity, (d) Duration.

For the quality parameter, the findings echoed the observations made regarding force perception, as seen in Figure 7 (b), with the ERM actuator exhibiting underwhelming performance across all evaluated effects regarding quality value. Among the LRAs tested, the LRA-3 demonstrated cleaner sensations than the ERM, followed by the LRA-2 and then the LRA-1, which was perceived as cleaner overall. An interesting exception was noted in the evaluation of the ramp vibration effect. In this scenario, the LRA-1 outperformed all other actuators, delivering significantly better quality than the others, even if it was perceived as weaker than the other two in the Force parameter.

Finally, examining scales of reactivity and duration, the test returns mixed results, as seen in Figure 7 (c-d), with no notable differences between actuators in terms of user perception, with the exclusion of the ERM that again performed poorly on both parameters on all the effects. All the LRAs performed similarly, with results close between them and no notable difference observed. Concerning the thinking-aloud test, the most used adjectives for each actuator were analysed, as shown in Figure 8. They mirror the survey results, with the ERM actuator performing poorly and mostly described as "imperceptible" or "no feedback." This leads to frustration in some subjects who expect different feedback. Regarding the LRAs, the LRA-1 and LRA-2 perform similarly, with mixed results and generally have been perceived better than the other, with slightly better performance for the LRA-2 than the LRA-1. The LRA-3 was perceived as average, more "dirty" and "buzzy" than the other LRAs, and generally less powerful.


**Figure 8**: Word clouds of the thinking-aloud test.

## 4.2 Discussion

The test on haptic actuators for automotive touchscreen interfaces provided insights into the performance and user perception of different haptic effects. Across our different parameters, such as force, quality, reactivity, and duration, the LRA actuators performed way better than the ERM one, mainly regarding force and quality perception. The ERM actuator consistently performed poorly, with users reporting low perception of force and overall quality, leading to frustration among some participants. This was because the ERM employed in the evaluation was too weak for the dimensions of the touchscreen analysed. Instead, among the LRAs, there were nuanced differences in performance. Users tended to perceive actuators with the oscillating axis parallel to the touch direction (like in the case of LRA-1 and LRA-2) better regarding force and quality, with slight differences between the two that changed according to the haptic effect addressed. The LRA-3 exhibited mixed results, with users perceiving it as less powerful and slightly less clean than other LRAs, even if capable of higher vibration forces than the other LRAs. We think this was due to its vibration axis and the screen assembly, which did not transmit the vibration well to the subject's fingers.

Apart from the ERM, all the LRAs performed similarly regarding the reactivity and duration scales. We conclude that the differences between the actuators were too subtle to be perceived by the subjects involved in the test. The talk-aloud part of the test further corroborated this, as the subjects tended not to speak of these parameters during the test but instead focused more on elements like "buzziness" and the perceived force of the vibration.

## 5 CONCLUSIONS

In our evaluation of four types of actuators for automotive touchscreen interfaces, linear actuators outperform the Eccentric Rotating Mass. Particularly among the LRAs, those operating along the z-axis exhibit superior performance, primarily due to users' enhanced perception of force. However, it is noteworthy that while actuators operating on the zeta-axis often demonstrate favourable outcomes, this was not always the case. This variability in the results highlights the difficulties and complexities of analysing something multifaceted, such as haptic touch feedback. Due to this nuanced nature, we think focusing only on the actuator's characteristics, specifically in the actuator's selection phases, could not guarantee a successful user experience. Still, instead, a heuristic approach could be better suited.

Furthermore, incorporating user-centred design and conducting extensive usability testing throughout development could be more beneficial. These could provide valuable insights into user preferences and behaviours, further refine haptic feedback mechanisms' refinement, and ensure better user experiences. Suppose the study extends to more advanced prototypes that are closer to the actual context of use. In that case, it might be beneficial to employ summative tests to evaluate the ease of interaction, as described in [16].

We also strongly acknowledge the test's limitations, including the small sample size and potential biases inherent in internal participants. Future studies could involve a more extensive and diverse participant pool to limit this. Additionally, by incorporating more sophisticated assessment techniques like electroencephalography (EEG), skin conductance response (SCR), and electrocardiography (ECG), deeper insights into the perceived effects of haptics on the driving user experience could be achieved.

This paper offers valuable insights into selecting and evaluating haptic actuators for automotive touchscreen interfaces. By considering factors beyond the mere characteristics of actuators, researchers and designers should incorporate extensive qualitative user feedback to refine haptic feedback systems in the future. This would enhance user experience and interface intuitiveness to improve driving experiences in the automotive sector.

## ACKNOWLEDGEMENTS

This research was supported by the AXD Lab – Politecnico di Milano. The authors thank everyone who participated in our study for their valuable time and insights.

## REFERENCES

[1] Arduino® Nano 33 IoT Datasheet: https://docs.arduino.cc/resources/datasheets/ABX00027-datasheet.pdf.

[2] Basdogan, C.; et al.: A Review of Surface Haptics: Enabling Tactile Effects on Touch Surfaces. IEEE Transactions on Haptics. 13, 3 (Jul. 2020), 450–470. https://doi.org/10.1109/TOH.2020.2990712.

[3] Beruscha, F.; et al.: An evaluation of the influence of haptic feedback on gaze behavior during in-car interaction with touch screens. 2017 IEEE World Haptics Conference (WHC) (Jun. 2017), 201–206.
[4] Bradford, J.H.; The human factors of speech-based interfaces: a research agenda. ACM SIGCHI Bulletin. 27, 2 (Apr. 1995), 61–67. https://doi.org/10.1145/202511.202527.
[5] Breitschaft, S.J.; et al.: A Theoretical Framework of Haptic Processing in Automotive User Interfaces and Its Implications on Design and Engineering. Frontiers in Psychology. 10, (Jul. 2019), 1470. https://doi.org/10.3389/fpsyg.2019.01470.
[6] Burke, J.L.; et al.: Comparing the effects of visual-auditory and visual-tactile feedback on user performance: a meta-analysis. Proceedings of the 8th international conference on Multimodal interfaces (New York, NY, USA, Nov. 2006), 108–117.
[7] Burnett, G.E.; Mark Porter, J.: Ubiquitous computing within cars: designing controls for non-visual use. International Journal of Human-Computer Studies. 55, 4 (Oct. 2001), 521–531. https://doi.org/10.1006/ijhc.2001.0482.
[8] Buxton, W. 1990. A Three-State Model of Graphical Input. (1990).
[9] Coe, P.; et al.: A Universal Volumetric Haptic Actuation Platform. Multimodal Technologies and Interaction. 7, 10 (Oct. 2023), 99. https://doi.org/10.3390/mti7100099.
[10] Costes, A.; et al.: Towards Haptic Images: A Survey on Touchscreen-Based Surface Haptics. IEEE Transactions on Haptics. 13, 3 (Jul. 2020), 530–541. https://doi.org/10.1109/TOH.2020.2984754.
[11] DRV2605L Datasheet: https://cdn.sparkfun.com/datasheets/Robotics/drv2605l.pdf.
[12] Gaffary, Y.; Lécuyer, A.: The Use of Haptic and Tactile Information in the Car to Improve Driving Safety: A Review of Current Technologies. Frontiers in ICT. 5, (Mar. 2018), 5. https://doi.org/10.3389/fict.2018.00005.
[13] Gaspar, A.A.: Design and evaluation of haptic feedback for in-vehicle touch screens. (2011).
[14] Haile, L.; et al.: 2015. The Affective Response to Exercise. Perceived Exertion Laboratory Manual: From Standard Practice to Contemporary Application. L. Haile et al., eds. Springer. 29–40.
[15] Harvey, C. and Stanton, N. 2013. Usability Evaluation for In-Vechicle Systems.
[16] ISO 20282-1:2006: https://www.iso.org/standard/34122.html. Accessed: 2024-05-28.
[17] Kang, J.C.: Opinion | Touch Screens in Cars Solve a Problem We Didn't Have. The New York Times.
[18] Kern, D.; Pfleging, B.: Supporting interaction through haptic feedback in automotive user interfaces. Interactions. 20, 2 (Mar. 2013), 16–21. https://doi.org/10.1145/2427076.2427081.
[19] Laugwitz, B;. et al.: Construction and Evaluation of a User Experience Questionnaire. HCI and Usability for Education and Work. A. Holzinger, ed. Springer Berlin Heidelberg. 63–76.
[20] Lee, J.-H.; Spence, C.: Assessing the benefits of multimodal feedback on dual-task performance under demanding conditions. Proceedings of the 22nd British HCI Group Annual Conference on People and Computers: Culture, Creativity, Interaction - Volume 1 (Swindon, GBR, Sep. 2008), 185–192.
[21] Material Design: https://m2.material.io/design/platform-guidance/android-haptics.html#principles. Accessed: 2024-01-29.
[22] Murali, P.K.; et al.: Intelligent In-Vehicle Interaction Technologies. Advanced Intelligent Systems. 4, 2 (2022), 2100122. https://doi.org/10.1002/aisy.202100122.
[23] Norman, D. 2013. The Design of Everyday Things. (2013).
[24] Park, S.; et al.: Vibrotactile rendering on a touch surface with reduced sound radiation. Journal of Sound and Vibration. 497, (Apr. 2021), 115936. https://doi.org/10.1016/j.jsv.2021.115936.
[25] Pitts, M.J.; et al.: Assessing subjective response to haptic feedback in automotive touchscreens. Proceedings of the 1st International Conference on Automotive User Interfaces and Interactive Vehicular Applications (Essen Germany, Sep. 2009), 11–18.

[26] Pitts, M.J.; et al.: Does haptic feedback change the way we view touchscreens in cars? International Conference on Multimodal Interfaces and the Workshop on Machine Learning for Multimodal Interaction (Beijing China, Nov. 2010), 1–4.
[27] Pitts, M.J.; et al.: 2Visual–haptic feedback interaction in automotive touchscreens. Displays. 33, 1 (Jan. 2012), 7–16. https://doi.org/10.1016/j.displa.2011.09.002.
[28] Playing haptics: https://developer.apple.com/design/human-interface-guidelines/playing-haptics. Accessed: 2024-01-29.
[29] ProtoPie: High-Fidelity Prototyping for Mobile, Desktop, Web & IoT: https://www.protopie.io/. Accessed: 2024-01-30.
[30] Regan, M.A.; Hallett, C.: Chapter 20 - Driver Distraction: Definition, Mechanisms, Effects, and Mitigation. Handbook of Traffic Psychology. B.E. Porter, ed. Academic Press. 275–286.
[31] Richter, H. et al.: HapTouch and the 2+1 state model: potentials of haptic feedback on touch-based in-vehicle information systems. Proceedings of the 2nd International Conference on Automotive User Interfaces and Interactive Vehicular Applications (Pittsburgh, Pennsylvania, Nov. 2010), 72–79.
[32] Schneider, O.; et al.: Haptic experience design: What hapticians do and where they need help. International Journal of Human-Computer Studies. 107, (Nov. 2017), 5–21. https://doi.org/10.1016/j.ijhcs.2017.04.004.
[33] The power of touch | Nissan Stories | Nissan Motor Corporation Global Website: 2021. https://www.nissan-global.com/EN/STORIES/RELEASES/ariya-haptic/. Accessed: 2024-03-20.
[34] The Rise of Touch Screens in Cars Explained: 2021. https://www.theturnsignalblog.com/blog/touch-screens/. Accessed: 2024-01-22.
[35] Weddle, A.B.; Yu, H.: Confirmation Haptics for Automotive Interfaces. (2013).