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# Hybrid Haptic Device for Car Door Interactions: User Perception of Torque Profiles

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***Abstract*— Car doors are the first and last points of physical interaction between users and vehicles, and their kinesthetic haptic feedback plays a key role in shaping user perception of vehicle quality. Therefore, optimizing the haptic feedback of car doors is essential for improving the overall user experience. This study investigates how car door torque profiles, determined by the mechanical components of the car door, influence user perception. A hybrid haptic device was developed to replicate various car door torque profiles and simulate realistic opening and closing experiences. Using this device, participants evaluated different virtual car doors with modified torque profiles and identified the profile that most closely resembled the sensation of a real car door. The base condition, which matched the torque profile of the reference car door, was rated as providing the most realistic and familiar experience. The results demonstrated that users are highly sensitive to changes in torque intensity and shape. These findings suggest that car door haptics significantly impact user experience, and strategic optimization of kinesthetic feedback can create a lasting impression on human-vehicle interactions.**

***Keywords—hybrid haptic device, car door haptics, torque profile, user evaluation, kinesthetic haptic feedback***

## I. Introduction

With the advancement of technology, research has shifted its focus from merely improving performance to enhancing emotional and sensory experiences. Human-Robot Interaction (HRI) is the study field of examining how humans interact with robotic systems, aiming to optimize usability and satisfaction [1]. Within this domain, haptics emerged as an important field of tactile and kinesthetic interactions between humans and systems [2, 3]. To advance and optimize haptic interaction, extensive research has been conducted on haptic devices that convey virtual haptic feedback [4-7].

Following this trend, the automotive industry has widely implemented haptic technologies to enhance user experiences in interfaces such as gearshift levers [8] and haptic display [9]. Among these, the car door is a critical component that marks the beginning and end of user interaction with the vehicle. The kinesthetic haptic feedback of car doors contributes significantly to the user perception of vehicle quality. However, replicating the haptics of car doors through haptic devices poses several challenges due to their complex dynamics. Car door dynamics are characterized by high torque requirements, often exceeding 50 Nm, and the asymmetric haptic experience during door opening and closing [10-12]. Consequently, developing specialized haptic devices and methods is essential for realistic car door rendering [13, 14].

We addressed these challenges by developing a hybrid haptic device specifically designed to replicate the torque profiles of car doors [15]. This system integrates a servo motor to simulate active torque and a magnetic powder brake to simulate passive torque, effectively separating the two components of car door dynamics. The hybrid device demonstrated its ability to provide stable and realistic torque rendering, even during rapid reversals in rotational direction.

In this study, the developed haptic device is utilized to conduct user evaluation investigating how torque profiles influence user perceptions of virtual car door interactions. The objectives are as follows:

1. To assess whether users can distinguish between variations in torque profiles.
2. To determine whether the base condition, implemented with the torque profile and moment of inertia matched to those of a real car, most closely resembles the haptic experience of a real car door.

Through user evaluation, the study revealed that users can perceive variations in torque profile. Furthermore, during the evaluations, participants described the haptics of each virtual door using physical expressions such as “heavy” and “stiff” as well as emotional expressions such as “smooth” and “cheap.” These findings suggest that car door haptics can significantly influence user physical and emotional perceptions and highlight the potential for optimizing haptic design to match user preferences through the thoughtful engineering of car door dynamics.

## II. Car Door Dynamics

Fig. 1(a) illustrates the dynamics of a car door during user operation. The torque applied by the user is denoted as $\tau_{ext}$, while the torque resulting from the internal components of the car door is represented as $\tau_{int}$. The net torque generated by $\tau_{ext}$ and $\tau_{int}$ induces rotational acceleration of the door, which can

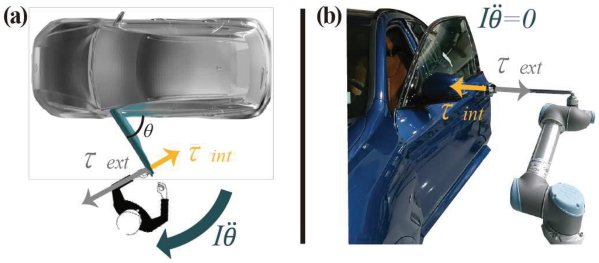


**Fig. 1.** (a) Car door dynamics. (b) $\boldsymbol{\tau_{profile}}$ measurement

be expressed by the following equation:

$$\tau_{ext} + \tau_{int} = (I_{car\ door})\ddot{\theta} \qquad (1)$$

The external torque $\tau_{ext}$ varies depending on the user. In contrast, the $\tau_{int}$ can be modified through the design of the mechanical components constituting the car door. This internal torque significantly influences the kinesthetic haptic perception experienced by the user during interaction with the door. Fig. 1(b) presents the experimental setup used to measure $\tau_{int}$. To eliminate the effects of inertia (specifically the angular acceleration), a robotic arm was used to operate the door at a constant angular velocity. The torque curve obtained as a function of the angle were defined as the torque profile ($\tau_{profile}$).

Fig. 2(a) shows the torque profiles of the driver-side door from Vehicle A, measured while opening and closing at a constant angular velocity of $1^o/s$. The yellow curve represents the torque during opening, and the blue curve represents the torque during closing. Positive torque is defined as acting in the direction of door closure, indicating that users primarily experience resistive forces during interaction with the door (positive regions in the yellow curve and negative regions in the blue curve).

$\tau_{profile}$ reveals several unique characteristics of the car door:

- Fluctuations in Torque: The profile exhibits three significant fluctuations, with specific sections where the door rotates autonomously.
- High Torque Requirements: A peak torque of approximately 50 Nm is required for operation.
- Asymmetric haptic experience: The torque profiles for opening and closing are different.

These features are primarily influenced by the door check [16, 17], a mechanical component designed to stabilize and control door movement. The door check serves three main purposes:

- Holding the door at specific angles to prevent over-rotation, allowing comfortable user entry and exit.
- Assisting door movement at specific angles to enable smooth opening and closing.
- Preventing sudden door movements, ensuring safety for users and those nearby.

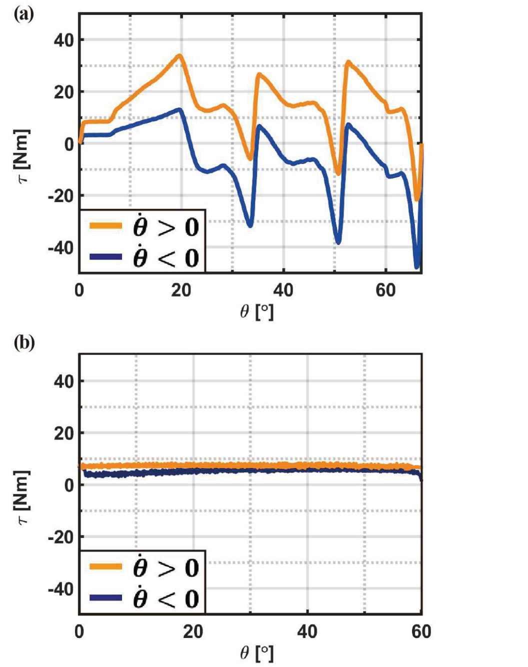


**Fig. 2.** (a) $\boldsymbol{\tau_{profile}}$ of Vehicle A. (b) $\boldsymbol{\tau_{profile}}$ of Vehicle A without checker assembly.

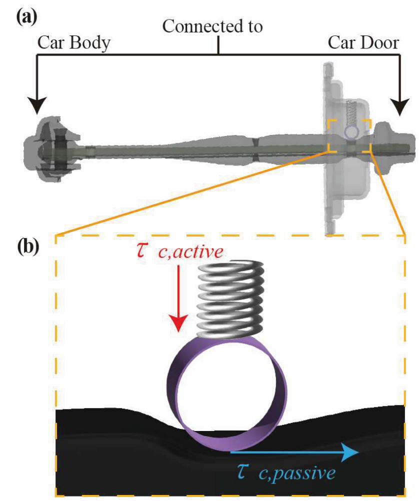


**Fig. 3.** (a) Internal structure of door check. (b) Two types of torque within $\boldsymbol{\tau_c}$.

Fig. 2(b) illustrates the torque profile after removing the door check. The torque remains nearly constant at approximately 7 Nm during both opening and closing. Due to the inclined rotational axis of the car door, gravitational torque generates resistive torque during opening and self-closing torque during closing. Minor differences between the opening and closing profiles are attributed to frictional torque generated at the door hinges. These results confirm that the main characteristics of car door torque profile are caused by the door check. Therefore, the design of the door check plays a crucial role in shaping the kinesthetic force feedback experienced by users, enabling significant modifications to the haptic characteristics of car doors.

Fig. 3(a) illustrates the internal structure of the door check. One end of the door check is attached to the car body, while the other end is connected to the car door. The torque generated by the door check is defined as $\tau_c$ . The door check consists of a roller (or slider) linked to a spring, which moves along the uniquely curved surface of the checker arm as the door rotates, thereby producing $\tau_c$.

Fig. 3(b) shows the two torque components of $\tau_c$:

1. Frictional Torque: This torque is generated between the roller (or slider) and the surface of the checker arm.
2. Spring-Generated Torque: On the upward slope of the checker arm, the spring compresses, generating resistive torque. Conversely, on the downward slope, the spring restores, generating torque that accelerates door rotation.

## III. Hybrid Haptic Device For Car Door Rendering

Torque can be classified into active torque and passive torque based on its role in rotational motion [18]. Active torque refers to the torque that induces rotation in the system. In the car door torque profile, gravitational torque and spring-generated torque from the door check are active torque components. These torques produce a consistent profile regardless of the direction of rotation. For example, gravitational torque always acts in the closing direction, offering resistance when opening the door and assisting rotation when closing it. Similarly, the spring torque in the door check provides resistance on the upward slope of the checker arm and aids rotation on the downward slope.

Passive torque, on the other hand, dissipates energy and serves to decelerate rotation or maintain a stationary state. Examples include frictional torque at the hinges and the friction between the checker arm and the roller or slider in the door check. Passive torque always opposes motion, resulting in two distinct profiles depending on the direction of rotation.

Considering these characteristics, the torque profile can be expressed as follows:

$$\tau_{profile,\,\dot{\theta}>0} = \tau_{active} + \tau_{passive} \tag{2}$$

$$\tau_{profile,\,\dot{\theta}<0} = \tau_{active} - \tau_{passive} \tag{3}$$

By combining these two equations, $\tau_{active}$ and $\tau_{passive}$ can be separated:

$$\tau_{active} = \frac{\tau_{profile,\,\dot{\theta}>0} + \tau_{profile,\,\dot{\theta}<0}}{2} \tag{4}$$

$$\tau_{passive} = \frac{\tau_{profile,\,\dot{\theta}>0} - \tau_{profile,\,\dot{\theta}<0}}{2} \tag{5}$$

Fig. 4 shows active torque profile and passive torque profile. The red curve represents $\tau_{active}$, which follows a single profile regardless of whether the door is being opened or closed. In contrast, the blue curve represents $\tau_{passive}$, which has opposite directions for opening and closing, resulting in two symmetric profiles about the x-axis. The influence of $\tau_{passive}$ , which changes direction based on the rotation, explains the asymmetry observed in the torque profile during door opening and closing.

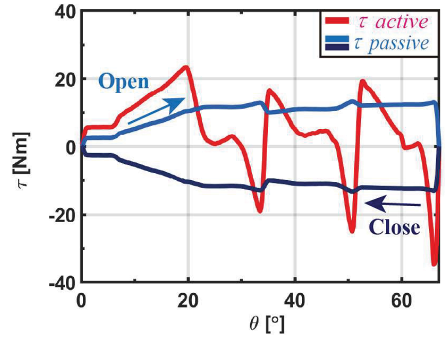


**Fig. 4.** $\boldsymbol{\tau_{active}}$ and $\boldsymbol{\tau_{passive}}$ in $\boldsymbol{\tau_{profile}}$ of Vehicle A.

Similarly, an actuator can be classified as a passive actuator and an active actuator based on their functional roles [19, 20]. The passive actuator is a device that always provides resistive forces to decelerate or control the motion of a system. Examples include brakes and dampers, which act in the direction opposite to the motion. On the other hand, the active actuator is a device that generates motion within a system. A motor is a representative example, converting electrical energy into rotational motion.

Based on these characteristics, the components of a torque profile can be implemented without stiffness issues by controlling the $\tau_{active}$ to a motor and $\tau_{passive}$ to a brake. This separation allows for precise replication of the torque profile with guaranteeing system stability.

Fig. 5 illustrates the hybrid haptic device designed for car door haptic rendering. Fig. 5 (a) and (b) present the CAD model and the fabricated hybrid haptic device, respectively. The device consists of a magnetic powder brake (maximum output: 50 Nm) for rendering the passive torque and a servo motor (maximum output: 54 Nm) for implementing the active torque in the car door torque profile. A torque sensor is mounted on top of the actuator to enable feedback control of the actuator output. The device is equipped with an actual car door handle, which can move vertically to emulate the dynamics of various car models.

Fig. 5 (c), (d), and (e) show the control circuit for implementing the car door torque profile. The core of the system is the microcontroller unit (MCU, Teensy 4.1), which governs signal processing and control. The encoder connected to the servo driver provides the door angular position, which the system uses to compute the corresponding torque profile values. These values are divided into active torque and passive torque and output as control signals to the motor and brake controllers, respectively. Additionally, feedback signals from the torque sensor and the servo driver feedback system ensure that the actuators deliver precise torque output. This system is designed to rapidly and accurately replicate the door dynamics of various car models.

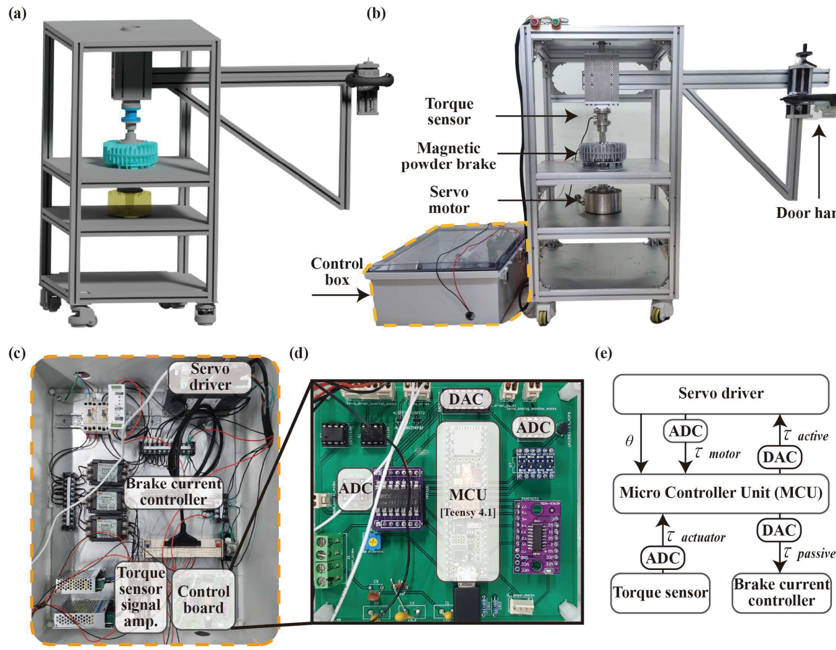


**Fig. 5.** (a) CAD(Computer-aided design) model of the hybrid haptic device. (b) Developed hybrid haptic device. (c) Internal configuration of the control box (d) Control board layout and components. (e) Control system diagram.

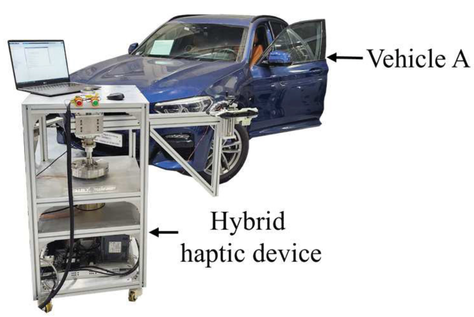


**Fig. 6.** User evaluation setup.

## IV. User Evaluation

The dynamics generated as the user operates the hybrid haptic device can be expressed as Equation (6):

$$\tau_{ext} + \tau_{device} = (I_{device})\ddot{\theta} \quad (6)$$

Similar to Equation (1), $\tau_{ext}$ represents the torque applied by the user to the haptic device, $\tau_{device}$ represents the virtual $\tau_{profile}$ implemented by the haptic device, and $(I_{device})\ddot{\theta}$ represents the inertial torque of the haptic device resulting from the net torque of these two components. For the user to experience the same haptic interaction as with a real car door (i.e., the same device motion($\ddot{\theta}$) occurs for the same applied torque($\tau_{ext}$)), it is essential to match both the $\tau_{profile}$ and $I_{car\ door}$.

To investigate whether users can perceive changes in $\tau_{profile}$, user evaluations were conducted. The real car door and the haptic device implementing the virtual door were placed side by side, allowing users to repeatedly compare them by opening and closing both. Users were then asked to rate the similarity score of the virtual door to the real car door(Vehicle A). Additionally, participants provided descriptive feedback on the similarities and differences between each virtual door and the real car door. The experiments were performed in compliance with the Korea Advanced Institute of Science and Technology (KAIST) IRB Protocol #KH2024-117.

In user evaluation, the moment of inertia ($I_{car\ door}$) was fixed, and only the torque profile ($\tau_{profile}$) was varied to investigate its impact on user perception. The following hypotheses were tested in this evaluation:

- Users will be able to distinguish between the haptic interaction of the real car door and the virtual car door with modified torque profiles (e.g., scaled or derived from different vehicles).
- The virtual door implemented with the base condition (mathing $\tau_{profile}$ of the real car door) will be rated as the most similar to the real car door.

### 1) *Participants*

A total of 21 participants (13 male, 8 female) aged between 20 and 40 years (mean age: 26.1 years) took part in the study. The participants represented diverse backgrounds, including engineering and humanities, to ensure a wide range of perspectives.

### 2) *Protocol*

Seven different torque profiles were evaluated in this study. Table I summarizes the virtual doors implemented in the haptic device for user evaluation.

The first virtual door (Virtual Door No. 1) was implemented as the base condition, replicating the same torque profile of the

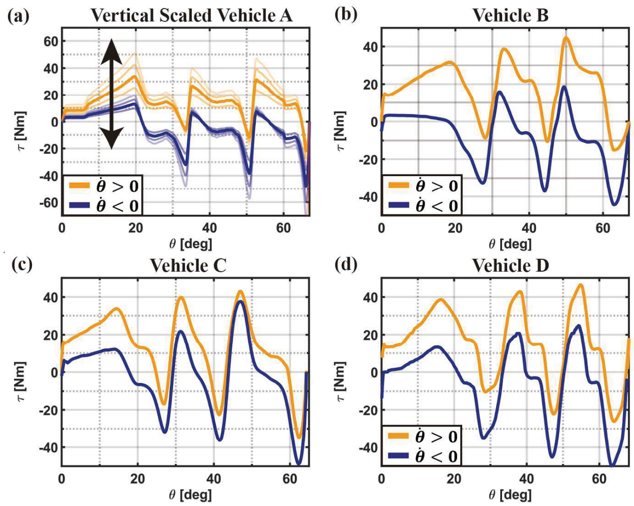


**Fig. 7.** $\boldsymbol{\tau_{profile}}$ of each vehicle. (a) Vehicle A with $\pm 25\%$ and +50% scaling adjustments. (b) Vehicle B. (c) Vehicle C. (d) Vehicle D.

reference car door. Virtual Door No. 2 featured the same overall shape as the reference car door torque profile but was scaled down by 25%. Virtual Doors No. 3 and No. 4 were scaled up by 25% and 50%, respectively. Virtual Doors No. 5, No. 6, and No. 7 used torque profiles measured from different vehicle models. The detailed torque profiles are shown in Fig.7.

Each participant repeatedly opened and closed both the real car door and each virtual door implemented in the haptic device. Participants were asked to rate the similarity of each virtual door to the real car door on a 10-point scale (quantitative evaluation). Additionally, they were instructed to provide qualitative feedback describing the similarities and differences between the real and virtual doors. To minimize distractions and ensure that participants focused solely on the haptic interaction, noise-canceling headphones were used to eliminate auditory cues.

TABLE I. VIRTUAL DOORS FOR USER EVALUATION

| **Virtual Door No.** | $\boldsymbol{\tau_{profile}}$ | ***Note*** |
|---|---|---|
| 1 | Vehicle A | Base condition |
| 2 | Vehicle A | -25% scaling down |
| 3 | Vehicle A | +25% scaling up |
| 4 | Vehicle A | +50% scaling up |
| 5 | Vehicle B | Different car door |
| 6 | Vehicle C | Different car door |
| 7 | Vehicle D | Different car door |

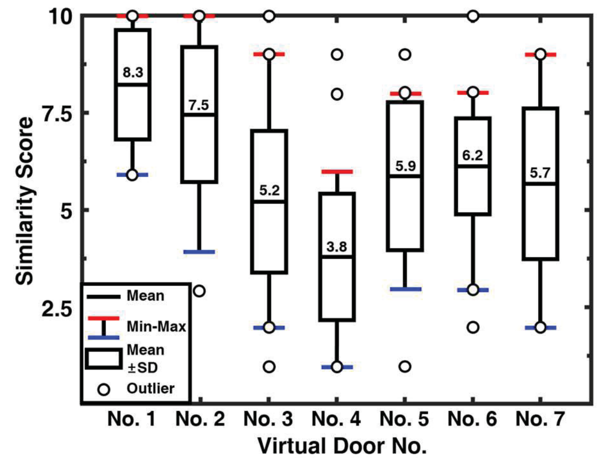


**Fig. 8.** User evaluations results.

### *3) Evaluation Results*

The evaluation results, summarized in Fig. 8, demonstrated several key insights into the effect of torque profile variations on user perception. The black line within each box represents the mean similarity score, while the box itself indicates the range of the mean ± standard deviation. The red and blue lines extending above and below the box represent the maximum and minimum scores, respectively. Small circles denote outliers, which are the top and bottom two scores for each condition. These outliers were excluded from the calculations for the mean and standard deviation to ensure more robust statistical analysis.

The virtual door implemented with the base condition (Virtual Door No. 1), which matched the torque profile of the reference car door, achieved the highest similarity score among all conditions, with a mean of 8.3. This result confirms that accurately replicating the torque profile of a real car door is essential for achieving high perceptual realism in car door rendering. The low standard deviation further indicates strong consensus among participants regarding the similarity of this condition to the real car door.

In contrast, the virtual doors with scaled-up torque profiles (Virtual Doors No. 3 and No. 4), which increased the torque by 25% and 50%, recorded significantly lower similarity scores, with means of 5.2 and 3.8, respectively. Participants consistently noted in their descriptive feedback that these doors required noticeably higher opening and closing torque compared to the real car door, making the difference easily perceptible. However, despite the increased torque magnitude, several participants observed that the overall shape of the torque fluctuation during door operation remained similar to that of the real car door. This suggests that while the absolute torque level significantly impacts perception, the characteristic pattern of resistance and fluctuation still contributed to a sense of similarity. Nevertheless, the excessive force requirement led to a clear perception of difference, as reflected in the significantly lower scores.

Virtual doors based on the torque profiles of different vehicle models (Virtual Doors No. 5, No. 6, and No. 7) received moderate similarity scores, ranging from 5.7 to 6.2. Participants reported that these profiles shared certain characteristics with the reference car door, such as the presence of three distinct fluctuations in the torque profile. However, differences in the angles and ranges where the door checker engaged were frequently cited as reasons for lower ratings compared to the base condition.

Interestingly, the virtual door with a scaled-down torque profile (Virtual Door No. 2) achieved a relatively high similarity score of 7.5. Participants explained that this condition was perceived as similar to the real car door because the angles and ranges of checker engagement closely resembled those of the reference car door. Unlike the scaled-up conditions, the scaled-down profile did not significantly deviate from the expected range of torque typically experienced in human-car door interactions, making it less perceptible as different. In descriptive responses, some participants noted that it felt almost identical to the real car door. However, when comparing it with the base condition, they judged the base condition to be more similar, which resulted in relatively lower scores for this profile. Overall, these results highlight sensitivity of users to torque profile variations, not only in terms of the magnitude but also the overall shape of the profile. The findings show the importance of accurately matching the torque profile to the real car door for achieving realistic haptic feedback.

## V. Conclusion and Future Work

In this paper, a hybrid haptic device was utilized to investigate how variations in torque profiles influence user perception of virtual car door interactions. The study successfully demonstrated that users can perceive changes in torque profile characteristics, such as intensity and shape, and that accurately replicating the torque profile of a real car door is critical for achieving high perceptual realism. By conducting user evaluations with fixed moment of inertia and varying torque profiles, the study identified the base condition—where the torque profile matched the reference car door—as providing the highest similarity score. Additionally, the study confirmed that deviations in torque profiles result in significant differences in user perception.

For future work, two key directions are proposed to further enhance the understanding and optimization of car door haptics:

1) investigating which parameters of torque profiles (such as the slope of fluctuations or peak torque) influence users emotional sensations

2) evaluating the impact of moment of inertia variations on user perception to complement torque profile studies.

For the first future work, it will be essential to study how specific adjustments to torque profile parameters influence the emotional responses of users during car door interactions. In the descriptive responses from user evaluations, participants used both physical descriptors, such as "heavy" and "stiff," and emotional descriptors, such as "smooth" and "cheap," when comparing the haptic sensations of each virtual door. These responses suggest that the careful design of torque profiles has

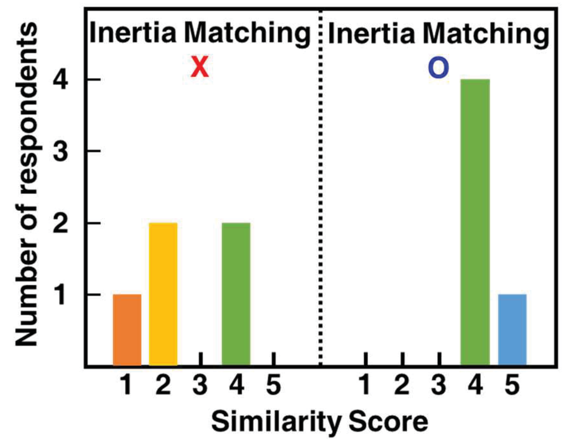


**Fig. 9.** Effect of inertia matching on user perception of car door haptics.

the potential to evoke specific emotional impressions and user preferences. By systematically analyzing how individual torque profile characteristics shape emotional sensations, future research could guide the design of haptic systems that enhance both functional realism and user satisfaction.

For the second future work, investigations into the effects of moment of inertia variations are necessary to better understand their role in shaping user perception. While this study focused on torque profile variations with the moment of inertia kept constant, preliminary experiments, as shown in Fig. 9, demonstrated that inertia significantly affected similarity scores, even when the torque profile remained identical to that of a real car door. In the evaluation, two conditions were compared: one where the moment of inertia was matched to the real car door and another where it was not. (Artificially attach a mass to the haptic device to create differences in inertia.) The results indicated that when inertia was matched, participants provided significantly higher similarity scores. Conversely, when inertia was mismatched, the similarity scores were lower, with participants reporting that the required force felt unnatural and that torque fluctuations were more noticeable. Additionally, participants noted that higher inertia increased the initial force required to rotate the door but resulted in smoother torque fluctuations. These findings indicate the importance of considering both torque profiles and inertia to achieve realistic and satisfying haptic feedback in car door design. Based on the preliminary experiment, future research should focus on evaluating the combined effects of these parameters, providing valuable insights for the optimization of haptic systems that align with user preferences and expectations.

## References


[1] T. B. Sheridan, "Human–robot interaction: status and challenges," *Human factors,* vol. 58, no. 4, pp. 525-532, 2016.

[2] K. Salisbury, F. Conti, and F. Barbagli, "Haptic rendering: introductory concepts," *IEEE computer graphics and applications,* vol. 24, no. 2, pp. 24-32, 2004.

[3] V. Hayward, O. R. Astley, M. Cruz-Hernandez, D. Grant, and G. Robles-De-La-Torre, "Haptic interfaces and devices," *Sensor review,* vol. 24, no. 1, pp. 16-29, 2004.

[4] S. Shin *et al.*, "Haptic simulation of refrigerator door," in *2012 IEEE Haptics Symposium (HAPTICS)*, 2012: IEEE, pp. 147-154.

[5] J. An and D.-S. Kwon, "Five-bar linkage haptic device with DC motors and MR brakes," *Journal of Intelligent Material Systems and Structures,* vol. 20, no. 1, pp. 97-107, 2009.

[6] S. Ha, L. Kim, S. Park, C. Jun, and H. Rho, "Virtual prototyping enhanced by a haptic interface," *CIRP Annals,* vol. 58, no. 1, pp. 135-138, 2009, doi: 10.1016/j.cirp.2009.03.015.

[7] J.-S. Yi, B.-J. Jung, and H. Moon, "Development of Simulator and Robotic Door for Parametric Design Optimization of Washing Machine Door Motion," *Journal of Korea Robotics Society,* vol. 12, no. 1, pp. 19-25, 2017, doi: 10.7746/jkros.2017.12.1.019.

[8] D. Chiaradia, M. Solazzi, D. Caporali, M. Russo, A. Piu, and A. Frisoli, "Haptic simulation of an automotive automatic gearshift: Stability analysis and design of force profiles with hysteresis," in *2016 IEEE International Conference on Robotics and Automation (ICRA)*, 2016: IEEE, pp. 2663-2668.

[9] Y. H. Heo, T.-H. Kim, D.-S. Choi, and S.-Y. Kim, "Head-Up Haptic Display Using Dual-Mode Haptic Actuator for Vehicles," *IEEE Transactions on Industrial Electronics,* vol. 71, no. 3, pp. 2779-2788, 2023.

[10] B. Anthonysamy, A. Nandi, P. Bhowal, and V. V. Chaudhari, "Passenger Car Door Closing Effort Prediction Using Virtual Simulation and Validation," SAE Technical Paper, 0148-7191, 2021.

[11] N. Kavthekar and A. Badadhe, "Numerical analysis of door closing velocity for a passenger car," *Int J Cybern Inf,* vol. 4, no. 2, pp. 1-16, 2015.

[12] M. Kena, D. Newton, J. P. Hakenberg, A. Ali, and A. Aljabr, "Calculate the cabin air bind effort on door closing efforts for passenger vehicle," in *Proceedings of the international conference on industrial engineering and operations management, Washington DC*, 2018.

[13] M. Strolz, C. Ehinger, and M. Buss, "Design of a device for the high-fidelity haptic rendering of rotatory car doors," in *2009 2nd Conference on Human System Interactions*, 2009: IEEE, pp. 202-209.

[14] M. Strolz, R. Groten, A. Peer, and M. Buss, "Development and Evaluation of a Device for the Haptic Rendering of Rotatory Car Doors," *IEEE Transactions on Industrial Electronics,* vol. 58, no. 8, pp. 3133-3140, 2011, doi: 10.1109/tie.2010.2087292.

[15] J. Ma, J.-S. Kim, and K.-U. Kyung, "A Hybrid Haptic Device for Virtual Car Door Interactions: Design and Implementation," *IEEE Robotics and Automation Letters,* 2024.

[16] S.-J. Kang and D.-H. Kim, "Door Effort Analysis for Hybrid Door Checker," *Transactions of the Korean Society of Automotive Engineers,* vol. 20, no. 3, pp. 52-57, 2012.

[17] K. Kwak, S. Kim, and K. Cho, "A Theoretical Study on the Profile of Door Checker Arm & Door Operating Force for Spring Roller & Hybrid Type," *한국자동차공학회 추계학술대회 및 전시회,* pp. 2247-2252, 2009.

[18] J. An and D.-S. Kwon, "Haptic experimentation on a hybrid active/passive force feedback device," in *Proceedings 2002 IEEE International Conference on Robotics and Automation (Cat. No. 02CH37292)*, 2002, vol. 4: IEEE, pp. 4217-4222.

[19] C. Rossa, J. Lozada, and A. Micaelli, "A new hybrid actuator approach for force-feedback devices," in *2012 IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2012: IEEE, pp. 4054-4059.

[20] C. Rossa, J. Lozada, and A. Micaelli, "Design and control of a dual unidirectional brake hybrid actuation system for haptic devices," *IEEE transactions on haptics,* vol. 7, no. 4, pp. 442-453, 2014.