Efficacy of Haptic Pedal Feel Compensation on Driving with Regenerative Braking

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Abstract—We study the efficacy of haptic pedal feel compensation on driving safety and performance during regenerative braking. In particular, we evaluate the effectiveness of the preservation of the natural brake pedal feel under two-pedal cooperative braking and one-pedal driving scenarios, through human subject experiments in a simulated vehicle pursuit task. The experimental results indicate that pedal feel compensation can significantly decrease the hard braking instances, improving safety for both two-pedal cooperative braking and one-pedal driving. Volunteers also strongly prefer compensation, while they equally prefer and can effectively utilize both two-pedal and one-pedal driving conditions. Furthermore, the beneficial effects of haptic pedal feel compensation is larger for the two-pedal cooperative braking case.

Index Terms—Regenerative braking, cooperative braking, one-pedal driving, haptic pedal feel compensation, force-feedback brake pedal.

I. INTRODUCTION

With the current emphasis on decreasing smog forming emissions, electric and hybrid vehicles are becoming ubiquitous. The electric motors on these vehicles assume dual purpose. Not only can they be used to accelerate the vehicle, but they can also be employed as generators to decelerate the vehicle. The use of electric motor for deceleration, by converting the kinetic energy of the vehicle into electrical energy to be stored in the battery, is called regenerative braking. Regenerative braking is crucial as it can significantly improve the range of the vehicle by improving its energy efficiency. Along these lines, it is desirable to employ regenerative braking as much as possible, while decelerating the vehicle.

During regenerative braking, the deceleration demand is measured based on a pedal displacement (as a signal) and appropriate resistance forces are applied to the vehicle through the electric motor to provide the desired deceleration level. However, there exists certain limitations of regenerative braking. The regenerative braking force depends non-linearly on the the speed of the vehicle, the state of the electrical motor and the charge level of the battery pack, at any given instant. Furthermore, regenerative braking can neither be applied at low speeds since sufficient braking forces cannot be generated, nor at high speeds since high voltages generated at these speeds may cause permanent damage to the battery. As a result, recruitment of conventional friction brakes along side with regenerative braking is necessary to ensure safe deceleration at any speed [1].

Conventional friction brakes are commonly implemented using (electro)hydraulics. When the brake pedal is pressed, hydraulic fluid is pushed into the master cylinder where the hydraulic forces are multiplied by a brake booster and send to the activate the brake pads. Consequently, the brake pads apply longitudinal forces to the discs to create friction between the discs and the brake pads. Thanks to the hydraulic fluid, there exists a physical power exchange between the brake pedal and the friction brakes, and whenever a driver pushes the pedal, she/he feels the reaction forces due to this physical coupling. While brake-by-wire systems can be employed to remove this physical coupling to improve reaction times and reduce overall complexity of the braking system, current vehicle safety regulations do not allow for the complete removal of the physical connection.

In this paper, a human subject experiment is conducted to test the efficacy of haptic pedal feel compensation on driving performance during cooperative braking. In a simulated vehicle pursuit scenario, a torque-controlled dynamometer is utilized for rendering the reaction forces due to friction braking, while an SEA brake pedal is employed to compensate for the disturbing effects of regenerative braking, to recover a natural brake pedal feel. The driving performance
of volunteers under regenerative braking with and without haptic pedal feel compensation, under one-pedal driving and two-pedal cooperative braking conditions are reported. This work significantly extends the preliminary user study presented in [12] by the addition of the dynamometer to render reaction forces due to the friction brake, the utilization of an accelerator pedal, the addition of the one-pedal driving condition and more extensive evaluations based on a new experimental protocol and multiple performance metrics.

II. EXPERIMENTAL SETUP

A. Series Elastic Brake Pedal

Figure 1 presents an exploded view of the series elastic brake pedal, whose initial design has been detailed in [12]. The device is actuated by a brushless DC motor equipped with an optical encoder to provide 1 Nm continuous torque output. A low-friction planetary gear train with 10:1 reduction is followed by a capstan transmission with 4:1 reduction, to amplify the torque output of the DC motor. The sector pulley of the capstan transmission is attached to brake pedal through a leaf spring based cross-flexure pivot that serves as a robust and simple compliant joint with a large deflection range. A Hall-effect sensor and a linear encoder are used for measuring the deflection of the cross-flexure pivot and estimating the interaction torques at the pedal. Once the interaction forces are estimated, closed-loop force control is implemented.

Thanks to its series elasticity, the force-feedback brake pedal can utilize robust controllers to achieve high fidelity force control, possesses favourable output impedance characteristics over the entire frequency spectrum, and can be implemented in a relatively compact package using low-cost components.

The SEA brake pedal used in this study features a force control bandwidth of 13 Hz for forces up to 75 N and can continually provide pedal forces over 200 N to the driver’s foot.

B. Haptic Pedal Feel Rendering Platform

Figure 2 presents a solid model of the haptic pedal feel rendering platform developed for testing different regenerative braking approaches. The system consists of a SEA brake pedal and a torque controlled dynamometer that share identical designs, as depicted in Figure 1. The two force feedback devices are mechanically coupled to each other through a rigid connection.

The dynamometer is used to render (electro)hydraulic friction brake reaction forces originating from the vehicles controllable master cylinder, as well as other forces/disturbances acting on the brake pedal, while the force-feedback pedal is used to implement cooperative braking algorithms to compensate for the disturbance effects and to recover the natural brake pedal feel.

![Fig. 1: Mechatronic design of the SEA brake pedal and the dynamometer](image)

Furthermore, to enable simulation of one-pedal driving, an open-loop impedance controlled throttle pedal is included to the system as presented in Figure 2. The throttle pedal consists of a direct drive motor with a 10:1 ratio capstan transmission such that forces up to 75 N can be provided to the driver’s foot.

C. Control of the Haptic Pedal Feel Rendering Platform

Figure 3 presents the block diagram used to control the haptic pedal feel rendering platform. In the figure, the thick lines denote power coupling and the thin lines represent signals. Symbols $m$ and $b$ denote the effective inertia and damping of the identical SEA devices. Human applied forces are indicated by two distinct components: $F_d$ representing the passive component and $F_{\text{act}}$ denoting the intentionally applied active component, which are assumed to be independent of the system states, such that coupled stability can be concluded through the frequency domain passivity framework [13].

In Figure 3, after appropriate scaling, the regenerative brake force demand $F_{\text{reg}}$ is passed to the SEA brake pedal as a reference force. The SEA pedal relies on closed-loop force control to ensure that this reference force is rendered to the driver with high fidelity. Similarly, the friction force brake demand $F_{\text{fric}}$ is passed to the dynamometer as a reference force such that (electro)hydraulic friction brake reaction forces originating from the vehicles controllable master cylinder are rendered to the driver. Consequently, the driver feels the force feedback from the total braking force applied to the vehicle, that is, the sum of forces from the friction brakes $F_{\text{fric}}$ through the dynamometer and forces from the regenerative brakes $F_{\text{reg}}$ through the SEA brake pedal.

The force/torque control of the brake pedal and the dynamometer are implemented as independent control loops, such that they can be run at different control rates and in an unsynchronized manner to be able to render more realistic disturbance and compensation forces. Independent real-time cascaded PI controllers are implemented for the control of series elastic actuators. In this cascaded controller, the fast inner-loop running at 2.5 kHz controls the velocity of the geared motor, rendering it into an ideal motion source by compensating for imperfections in the power transmission, such as friction and stiction in the gearbox. The outer-loop, implemented at 1 kHz, controls the interaction torque based on the deflection feedback from the compliant element. The coupled stability of the cascaded control architecture of SEA is guaranteed within the frequency domain passivity framework with the proper choice of controller gains, as detailed in [14].

![Fig. 2: Haptic pedal feel rendering platform for cooperative braking](image)
III. HAPTIC PEDAL FEEL COMPENSATION

In this section, pedal feeling rendering algorithms for two-pedal cooperative braking and one-pedal driving are detailed.

A. Conventional Haptic Brake Pedal Feel

The conventional haptic brake pedal feel to be recovered under the intervention of regenerative braking is mathematically modeled as

$$F_{\text{pedal}} \left[ N \right] = \begin{cases} 0.80 \ x_{\text{pedal}} + 18.17 & x_{\text{pedal}} \leq 20 \ \text{mm} \\ 3.92 \ x_{\text{pedal}} - 44.23 & 20 \ \text{mm} < x_{\text{pedal}} \leq 80 \ \text{mm} \end{cases}$$

where $x_{\text{pedal}}$ denotes the pedal displacement with a maximum stroke of 80 mm and $F_{\text{pedal}}$ is the total pedal force [15].

B. Brake Pedal Displacement to Deceleration Mapping

The brake pedal displacement $x_{\text{pedal}}$ is mapped to the deceleration demand $a_{\text{car}}^d$ according to the following function as proposed in [15].

$$a_{\text{car}}^d \left[ \text{m/s}^2 \right] = \begin{cases} -(0.01 \ x_{\text{pedal}})g & x_{\text{pedal}} \leq 20 \ \text{mm} \\ -(0.02 \ x_{\text{pedal}} - 0.2)g & 20 \ \text{mm} \leq x_{\text{pedal}} \leq 80 \ \text{mm} \end{cases}$$

where $g$ represents the gravitational acceleration.

C. Brake Pedal Force due to Friction Braking

To render the reaction forces on the brake pedal during friction braking, the brake pedal position is mapped to the dynamometer torque as

$$F_{\text{FrC}}^b \left[ N \right] = \begin{cases} 0.16 \ x_{\text{pedal}} + 3.63 & x_{\text{pedal}} \leq 20 \ \text{mm} \\ 0.78 \ x_{\text{pedal}} - 8.84 & 20 \ \text{mm} < x_{\text{pedal}} \leq 80 \ \text{mm} \end{cases}$$

where $F_{\text{FrC}}^b$ denotes the hydraulic friction braking forces applied by the dynamometer.

D. Brake Force Distribution

Brake force distribution is decided based on the deceleration demand $a_{\text{car}}^d$ from the driver, instantaneous vehicle speed $v_{\text{car}}$, battery charge level and the road conditions. A simple model of instantaneous regenerative braking force is employed as $F_{\text{reg}} = \frac{P_{\text{m}}}{v_{\text{car}}}$, where $P_{\text{m}}$ denotes the constant braking power of the electric motor, and $v_{\text{car}}$ is the instantaneous velocity of the vehicle [2]. Note that regenerative braking forces $F_{\text{reg}}$ cannot be generated below/above some critical speed, in particular, below 4 m/sec (15 km/h) and above 33 m/sec (120 km/h). To avoid inducing any sudden changes in regenerative braking force, linear interpolation is used around the critical speeds to smooth out the transition. The regenerative braking force to brake pedal force mapping is given as follows.

$$F_{\text{reg}}^b \left[ N \right] = \begin{cases} 0.0164 \ F_{\text{reg}} - 44.21 & F_{\text{reg}} \geq 2352 \ \text{N} \\ 0.0068 \ F_{\text{reg}} + 18.17 & 0 \ \text{N} \leq F_{\text{reg}} < 2352 \ \text{N} \end{cases}$$

Given the regenerative braking capacity at any instant and neglecting the road conditions for simplicity, the brake force distribution block determines the amount of regenerative and friction braking that needs to be employed, based on the one-pedal versus two-pedal driving condition.

Sample cooperative braking scenarios with and without haptic brake pedal feel compensation are presented for two-pedal and one-pedal driving in Figures 4(a) and 4(b), respectively. In the first row of the figures, the velocity of the vehicle is depicted, while the pedal displacement is presented in the second row. For the one-pedal driving case, the throttle displacement is also presented. In the third row, the regenerative braking forces, friction brake forces and total brake forces are depicted. The last row presents the pedal forces felt by the driver. In these sample scenarios, pedals are assumed to be displaced in a linear manner, for the simplicity of presentation.

1) Two-Pedal Cooperative Braking: In two-pedal cooperative braking, regenerative brake is activated by pressing the brake pedal. When there is a deceleration demand from the driver, the regenerative braking is utilized as much as possible. When the deceleration demand is higher than that can be supplied by the regenerative braking, the friction brake is activated. In the uncompensated case, there exists no pedal force due to regenerative braking, while in the compensated case, relevant pedal forces are rendered to the pedal as discussed in previous subsection.

In Figure 4(a), when the driver presses the brake pedal at $t = 5$ s, regenerative brake is employed to the maximum capacity. The regenerative braking forces increase in a nonlinear fashion, as the vehicle slows down. Note that no pedal force exists for the non-compensated case when friction brake is not in use. Since the regenerative braking forces cannot be generated at velocities lower than 4 m/sec, the friction brake is employed at $t = 16$ s such that the desired deceleration demand can be delivered. Starting this instant, brake pedal forces go through a sharp increase in the uncompensated condition until the friction brake takes over the whole braking at $t = 20$ s. After $t = 20$ s, the uncompensated pedal feels like a conventional friction brake. Note that the compensation eliminates the discontinuities and stiffening/softening of haptic pedal feel due to regenerative braking and delivers a continuous conventional brake pedal forces throughout the cooperative braking.

2) One-Pedal Driving: One-pedal driving and two-pedal cooperative braking differ in that regenerative braking is activated when the throttle pedal is released in one-pedal driving. In particular, when the driver releases the throttle pedal, the maximum available regenerative braking force is utilized until a threshold (chosen as 0.32g in this study) after which the force is saturated not to induce an uncomfortable deceleration level. If the driver presses the emergency brake pedal, further use of regenerative braking may be activated as in cooperative braking, while typically the friction brake is activated, as most capacity of regenerative braking is already in use. In the uncompensated case, there exists no pedal force due to regenerative braking, while in the compensated case, relevant pedal forces are rendered to the emergency brake pedal to achieve a linear relationship with the total braking force.

In Figure 4(b), the driver releases the throttle pedal at $t = 10$ s, which activates the regenerative braking, but does not render any forces to the emergency brake pedal in both cases, as it is not being pushed yet. The displacement of the emergency brake pedal
is increased linearly during \( t = 11\)–15 s and the friction brake is activated, as the deceleration from regenerative braking is not sufficient to provide the demanded deceleration. In the uncompensated case, the driver feels only the reaction forces from the friction brake. While this force is continuous, the mapping between the pedal force and the total brake force is nonlinear. In the compensated case, this mapping is linear.

IV. USER EVALUATIONS

A. Participants

Ten volunteers (8 males and 2 female) with ages between 22 to 28 participated in the experiment. All participants had active driver’s licenses and none of them had any prior experience with vehicles equipped with regenerative braking. All participants signed an informed consent approved by the IRB of Sabanci University.

B. Driving Simulator

The simulator setup consisted of an SEA brake pedal, a dynamometer, a throttle pedal and a vehicle simulator, as presented in Figure 5. Participants were seated in a vehicle seat and adjusted the seat position according to their preferred driving position. The simulator provided visual feedback through two flat screens displays. The front screen displayed the simulated vehicle pursuit scenario, while the left monitor showed the vehicle speed.

C. Task

The pursuit task is based on a simplified version of the Crash Avoidance Metrics Partnership (CAMP) protocol [16]. The simulation took place on a virtual straight road of 1500 m, where the controlled vehicle followed a leading vehicle. The leading vehicle accelerated at 0.2 g until it reached the target speed of 50 km/h. Once it reached 50 km/h the leading vehicle decelerated until stop, and then after waiting for a short random interval, it re-accelerated back to 50 km/h. In particular, the leading vehicle decelerated with 0.19 g, 0.28 g and 0.39 g at random instances within the 0–500 m, 500 m–1000 m, and 1000 m–1500 m stretches of the road. The leading vehicle stopped permanently at the end of the road.

Initially, the following vehicle was placed 15 m behind the leading vehicle. The volunteers operated the throttle for acceleration and SEA brake pedal for (emergency) braking. The volunteers were asked to keep a 30 m distance to the lead car.

D. Experimental Procedure

Effect of two main factors of compensation and pedal type are investigated. In particular the within-subjects experiment protocol involved two-pedal uncompensated, two-pedal compensated, one-pedal uncompensated and one-pedal compensated conditions tested on the same volunteers. At the beginning of experiments an unrecorded session was implemented, during which all four conditions were displayed to the volunteers in a randomized order to help them familiarize with the braking simulator. Then, volunteers were assigned to test conditions in a randomized order. The volunteers were informed about one pedal versus two pedal driving condition, but not about the existence/lack of compensation. After each trial, they were asked to recognize the existence of compensation.

![Virtual Reality Braking Simulator with a Vehicle Pursuit Task](image1)

![Haptic Pedal Feel Rendering Platform](image2)

**Fig. 5:** Cooperative braking simulator
E. Performance Metrics

Several quantitative metrics are defined to evaluate the driving performance of the participants. The number of times hard brakings were necessitated during the trials is selected as a performance metric, as large decelerations are potentially dangerous. In particular, decelerations over 0.5g are considered as hard braking [17].

For driving performance analysis, the distance between two vehicles is selected as the performance metric. In particular, % RMSE is calculated with respect to the instructed distance of 30 m.

To evaluate the energy efficiency of driving, regenerated energy of each session is calculated by adding the regenerative power at each time step. Furthermore, percent throttle use is also computed.

Finally, the volunteers are asked to fill in a short questionnaire to help evaluate their qualitative preferences among the test conditions. The questionnaire included nine questions as presented in Table I. A 5-point Likert scale is used to indicate preferences, where 5 denotes strong agreement and 1 denotes strong disagreement.

F. Analysis

Two-way repeated measures ANOVA is conducted to determine the significant effects on the quantitative metrics. The within-within factors are taken as compensation (compensated/uncompensated) and pedal type (two-pedal/one-pedal). Box plots of important metrics are present to enable multi-comparisons and effect size evaluations.

V. RESULTS

A. Quantitative Metrics

1) Safety: Figure 6(a) presents the box plot for the number of hard brakings. Two-way repeated measures ANOVA indicates that the interaction of compensation and pedal type factors is significant with $F(1,9) = 9.51, p = 0.014$. The compensation is significant, while the pedal type is not significant at the $p < 0.05$ level.

For the simple main effect analysis, the data is first split for two-pedal and one-pedal driving conditions. For the two-pedal driving condition, hard brakings in the compensated case ($M = 1.2, SD = 0.33$) are significantly lower than the uncompensated case ($M = 4.4, SD = 0.56$) with $F(1,9) = 39.05, p < 0.001$. The effect size is significant as the number of hard brakings have increased more than 3.5 times in the uncompensated case. Similarly, for the one-pedal driving condition, hard brakings in the compensated case ($M = 1.8, SD = 0.36$) are significantly lower than the uncompensated case ($M = 2.8, SD = 0.53$) with $F(1,9) = 5.63, p = 0.042$. The effect size is also significant as the number of hard brakings has increased by 55% in the uncompensated case.

The data is also split for compensated and uncompensated conditions. For the uncompensated condition, hard brakings instances in the two-pedal condition ($M = 4.4, SD = 0.56$) are significantly higher than the one-pedal case ($M = 2.8, SD = 0.53$) with $F(1,9) = 5.43, p = 0.045$. The effect size is significant as the number of hard brakings has increased more than 57% in the two-pedal case. For the compensated group, pedal type is not a significant factor at the $p < 0.05$ level.

2) Driving Performance: Two-way repeated measures ANOVA indicates that compensation, pedal type, and interaction are not significant factors for the % RMSE metric quantifying the tracking performance at the $p < 0.05$ level.

3) Energy Efficiency: Figure 6(b) presents the box plot for the percent throttle use. Two-way repeated measures ANOVA indicates that one-pedal driving ($M = 40.1, SD = 3.1$) results in significantly higher throttle use compared to two-pedal cooperative braking ($M = 25.86, SD = 4.25$) with $F(1,9) = 6.92, p = 0.034$. Compensation and interaction are not significant at the $p < 0.05$ level. The effect size is significant as the throttle use has increased by 60% in the one-pedal driving case.

Figure 6(c) presents the box plot for the regenerated braking energy. One-pedal driving ($M = 3.096, SD = 0.25$) results in significantly higher regenerated energy compared to two-pedal cooperative braking ($M = 1.035, SD = 0.045$) with $F(1,9) = 70.15, p < 0.001$, while compensation and interaction are not significant at the $p < 0.05$ level. The effect size is significant as 3 times more energy is regenerated during the one-pedal driving.

VII. DISCUSSION AND CONCLUSION

Safety is one the key aspect for evaluating the driving performance. The number of hard brakings is a commonly used safety metric, as it is important for the drivers to be able to predict the stopping distance and safely decelerate the vehicle accordingly. The addition of regenerative braking results in a nonintuitive brake pedal force to deceleration mapping that significantly reduces the driver performance in terms of the need for hard brakings. Given that the regenerative braking is highly nonlinear and strongly affected by the instantaneous state of the vehicle, long training periods may be necessary for drivers to adjust to this nonintuitive brake mapping. Compensation of haptic pedal feel recovers the natural brake pedal feel by removing the nonlinearities and the strong dependence to the instantaneous state. In the compensated case, there exists a linear mapping between the pedal force and the total braking force that results in a significant decrease in the need for hard brakings, for both one and two pedal driving conditions.

In terms of the number of hard brakings, compensation has a larger positive effect for the two-pedal cooperative braking. While in the compensated case, both one pedal and two-pedal case have similar...
In conclusion, compensation of haptic pedal feel has been shown to be advantageous, especially in term of safety and driver preferences, for both two-pedal cooperative braking and one-pedal driving. While the volunteers equally prefer and can effectively utilize both two-pedal and one-pedal driving conditions, the beneficial effects of haptic pedal feel compensation is shown to be larger for the two-pedal cooperative braking case.

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