Driver Foot Behavior with Regenerative Braking

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Abstract

With the increase of electric vehicles on the roads, there is also an increase with vehicles that use regenerative braking (RB). This novel braking method differs from traditional service braking (SB) because RB decelerates the moment the driver releases the accelerator pedal and continues to actively brake if neither pedal is depressed. Since the vehicle actively decelerates when neither pedal is depressed in a vehicle with RB, we hypothesized that this would result in a difference in driver foot behavior. There were two pieces to explore this potential difference.

The first piece was to explore time-based measures. The first measure was the time period from when the lead vehicle brake lights illuminate, to when the driver releases the accelerator pedal. The second measure was the time period from when the driver releases the accelerator pedal, to when the driver presses the brake pedal. When comparing RB and SB, there was no statistically significant difference for the first timebased measure. When comparing RB and SB for the second time-based measure, the high level of RB was statistically significantly different.

The second piece was to code each video to label driver foot behavior based on a set of categories. The 5 th category (uncertainty – "wagging foot") was the only foot behavior appearing in all three conditions (n=2, SB; n=4, low RB; n=6, high RB). The 8 th category (brake tap, reposition to throttle, then brake press), only appeared in the high level of RB condition and appeared 9 times (33% rate).

This study shows that RB results in differences in driver foot behavior when compared to SB in the time period between accelerator release and brake press. It also shows that RB results in drivers engaging in foot behavior indicating uncertainty.

Keywords: up to six keywords complementing title and abstract separated by semicolons; using Times New Roman 10pt.

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1 Introduction

With the increase of electric vehicles on the roads, a new braking system known as regenerative braking will also increase. Regenerative braking (RB) is a braking system used in electric and hybrid vehicles that recaptures the kinetic energy that is normally lost through heat when using conventional service brakes. When a driver releases the accelerator pedal, this results in the vehicle immediately decelerating beyond normal levels associated with coasting. The level of deceleration varies from vehicle type to vehicle type. Service brakes (SB) are the traditional braking systems found in internal combustion–powered vehicles. With conventional SB, the braking sequence is initiated by force applied to the brake pedal. When neither pedal is depressed, the vehicle coasts. RB alone is does not offer the same deceleration as SB. Therefore, all vehicles with RB as also equipped with SB.

Figure 1 is a state diagram that visualizes when regenerative braking is and is not active. In the diagram, "X" is defined as the point in which RB is triggered. Some vehicles this may be as pedal deflection of the accelerator pedal approaches zero. Other vehicles this may be once the accelerator is fully released. Since a vehicle with RB does not coast, and the driver must keep their foot on the accelerator to avoid the vehicle actively braking, it is necessary to explore the differences in driver foot behaviour.

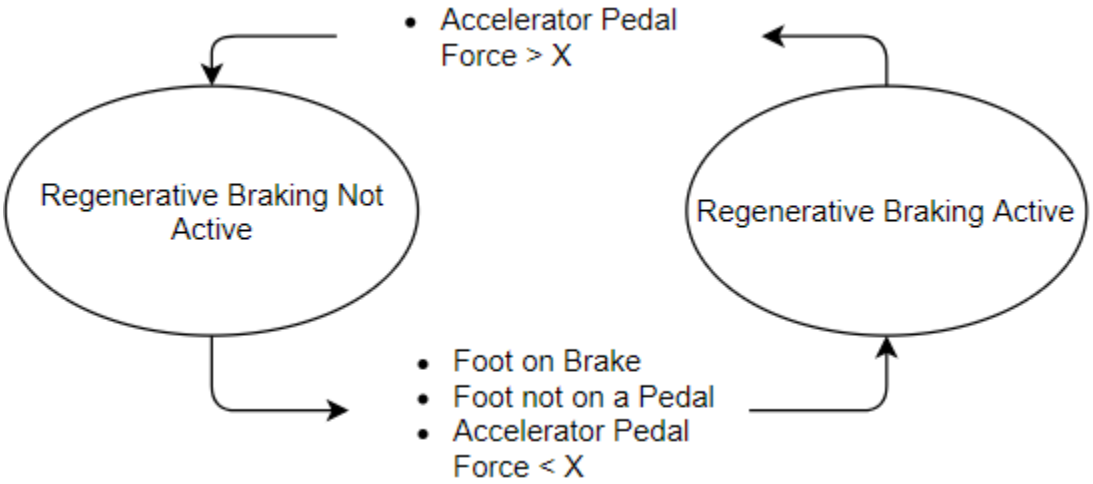

Figure 1: State diagram of Regenerative Braking.

1.1 Research Questions and Hypotheses

A central question regarding this behavior is whether there is a difference in driver foot behavior between RB and SB. This research compares driver foot behavior between a high and low level of RB—which is modelled after the RB observed in the Tesla Model S 75D—with standard SB. Theoretically, since a vehicle with RB actively decelerates when neither pedal is depressed, we hypothesize that driver foot behavior using RB will be different when compared to a driver using SB because with RB the car begins actively decelerating upon throttle release rather than upon brake press.

2 Methodology

2.1 Data

In order to analyze foot behavior, video data was sampled from a recent study [1]. This study explored three conditions of braking. The first was SB, the second was a low level of RB, and the third was a high level of RB. The low level of RB slowed the car at approximately -0.02 to -0.05 g, while the high level slowed the vehicle at approximately -0.15 to -0.2 g. Each participant participated in a simulated drive that consisted of three braking events while following a lead vehicle.

The original data set contained 30 participants, allocating 10 participants per condition (SB, low RB, or high RB). After quality checks of the data, one participant in the RB high condition had to be removed due to constant two-footed driving.

2.2 Equipment

The National Advanced Driving Simulator NADS-1 was used for this study. The NADS-1 utilizes a full-size vehicle cab and projects a virtual scene 360 degrees around the driver on the interior walls of the dome that houses

the cab. The vehicle dynamics are based on an Oldsmobile Intrigue, while RB was modeled from data collected from the NADS Tesla Model S 75D research vehicle.

2.3 Time-Based Measures

This paper used time-based measures to explore differences in braking behavior between SB and RB. Figure shows the timeline of driver behavior. At the beginning of an event, the lead vehicle turns its brake lights on. In response, the driver releases the accelerator pedal. At some later time, the driver presses on the brake pedal.

The first measure extracted from this timeline is the time period from when the lead vehicle brake lights turn on to when the driver releases the accelerator pedal. This measure is used to explore whether RB and SB differ in terms of the driver's reaction time. The second measure extracted from this timeline is the time period from when the driver releases the accelerator pedal to when the driver presses the brake pedal. This time period is significant, because this is when RB alters the braking process by actively braking instead of coasting.

Figure 2: Driver Behavior Braking Timeline.

2.4 Driver Foot Behavior Categories

In order to understand driver foot behavior, foot behaviors must be categorized. The categories used and the definitions of the categories are sampled from a 2016 study by McGehee et al. (2016), with the exception that one new category has been added for the sake of this study.

Table 1: Modified Foot Behavior Categorization.

#	Category	Definition
1	**Wrong pedal**	Driver pressed incorrect pedal.
2	**Miss**	Driver attempted to hit a pedal but missed it entirely.
3	**Both pedals pressed**	Driver pressed both pedals at the same time.
4	**Pedal slip**	Driver's foot slipped off either the brake or accelerator pedal and was then put back on the correct pedal.
5	**Uncertainty – "wagging foot"**	Driver wagged foot laterally (between or over brake and accelerator), in the z-direction—Z-wag (over gas pedal)—or a combination of the two at least two times in two directions, appearing to be unsure of which pedal to hit.
6	**Back pedal hook**	Driver catches the underside or side of brake pedal with foot when lifting off gas pedal.
7	**Near-miss, reposition of foot**	Driver moved foot from one pedal to another then quickly repositioned the foot on the pedal because it was a near miss.
8	**Brake tap, reposition to accelerator, then brake press (new)**	Driver displays an odd trajectory when transitioning between pedals.

The eighth category is brake tap, reposition to accelerator, then brake press. This measure was created after the first iteration of video coding and is the only new category. These phenomena where the driver would release the accelerator, either tap the brake or simply hover over it, return back to the accelerator and either tap or hover over it, and then finally move back to the brake for a full press only occurred in the high level of RB condition. Figure 2 visually shows what occurs in this category.

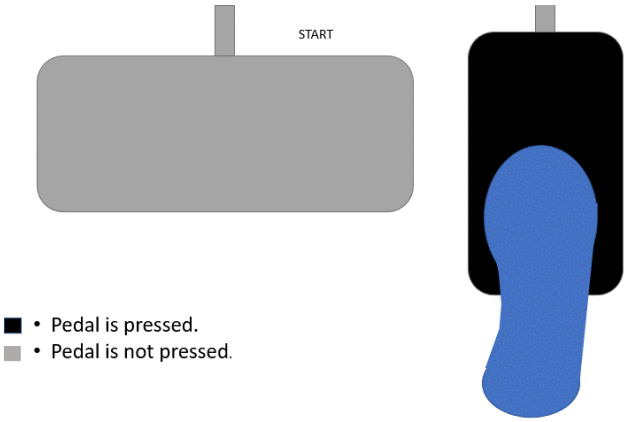

Figure 2: GIF Depicting the Eighth Category of Foot Behavior.

This new category also introduced the need for an adjustment in measuring accelerator release to brake press. The reasoning is that if the person tapped the brake before returning to the accelerator and then back for the full brake press, the system would stop the clock at that first brake tap. This tap was not actually the beginning of the driver's brake press, so instead it was adjusted so that the timer would stop when the driver returns to the brake for a full press.

3 Results

The video coding results showed three different measures appearing in the braking events. These measures were: measure five, the "wagging foot" or uncertainty; measure seven, near miss and reposition of the foot; and measure eight, brake tap, reposition to accelerator, then brake press. Table 2 shows how many times each measure appeared in the video, as well as the rate at which the measure appeared per condition.

Table 2: Video coding results.

	SB	**RBLow**	**RBHigh**	**Kruskal Wallis H**
N	30	30	27	
Uncertainty – "wagging foot" (5)	2 (7%)	4 (13%)	6 (22%)	p=0.5997
Near-miss, reposition of foot (7)	0 (0%)	1 (3%)	0 (0%)	p=0.96813
Brake tap, reposition to accelerator, then brake press (8)	0 (0%)	0 (0%)	9 (33%)	p=0.04651

It is important to note that the eighth measure (brake tap, reposition to accelerator, then brake press) appeared exclusively in the high RB condition. The sixth measure (uncertainty – "wagging foot") occurred with all the conditions, but was most prevalent in the high RB condition (SB, n=2; RBLow, n=4; RBHigh, n=6).

The Kruskal-Wallis H and Mann-Whitney U tests were used to compare means between levels of RB and SB. These tests were used because the data did not follow a normal distribution, and a non-parametric test was needed. If significance was found with Kruskal-Wallis H, indicating that at least one sample stochastically dominates the others, then Mann-Whitney U was used to see specifically which sample differs by testing every combination available.

Table 3: Time period between accelerator release and brake press.

Conditions		**SB, RBLow**	**SB, RBHigh**	**RBLow, RBHigh**	**SB, RBLow, RBHigh**
Kruskal-Wallis H/Mann-Whitney U		0.001	6.185	6.468	8.339
Degrees of Freedom		1	1	1	2
Asymptotic Significance		0.976	0.03	0.011	0.015

Table 3 shows the Kruskal Wallis H/Mann-Whitney U results for the time period from accelerator release to brake press. Asymptotic significance is the test for statistical significance. If asymptotic significance is less than 0.05, then one or more of the means being compared is statistically significantly different. When comparing all three conditions using Kruskal Wallis H, there was significance, meaning at least one sample was statistically

significantly different than the rest. Mann-Whitney U tests found the condition that was statistically significantly different was the high level of RB.

Kruskal Wallis H was also used to compare the time period from the lead vehicle's brake lights illuminating to the time the participant releases the accelerator pedal. Asymptotic significance shows there is no statistically significant difference between the three conditions.

4 Discussion

With the increase of electric vehicles on the roads, there is also an increase with vehicles that use regenerative braking. This novel braking method differs from traditional service braking because RB decelerates the moment the driver releases the accelerator pedal and continues to actively brake if neither pedal is depressed. SB coasts when the driver releases the accelerator pedal and until the brake pedal is depressed. This difference is represented in Figure 3. Since the vehicle with RB actively decelerates when neither pedal is depressed, rather than coasting like a vehicle with SB, we hypothesized that this would result in a difference in driver foot behavior.

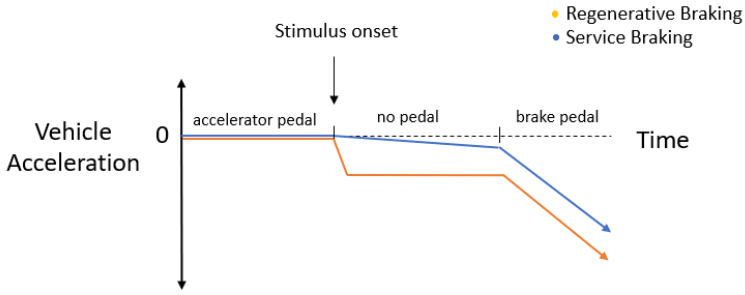

Figure 3: Vehicle Acceleration vs. Time.

When comparing the three conditions, there was not a statistically significant difference for the first time-based measure exploring the time period when the lead vehicle brake lights turn on to when the driver releases the accelerator pedal. This is understandable because the user does not get any feedback from RB until it is triggered, which in the case for this study is when the accelerator pedal is released.

When comparing the three conditions, significance was found for the second time-based measure exploring the time-period from when the driver releases the accelerator pedal to when the driver presses the brake pedal. The high level of RB was statistically significantly different than both the low level of RB and SB. This measure found that when using the high level of RB, drivers tend to spend more time with neither pedal depressed. This implies that the drivers were able to recognize that the vehicle was actively braking in this time period and delayed pressing on the brake pedal until the situation required it.

Coding each video to label driver foot behavior yielded some significant results. The 5th category (uncertainty – "wagging foot") was the only foot behavior appearing in all three conditions. This measure appeared twice in the SB condition (n=30; 7% rate), 4 times in the low RB condition (n=30; 13% rate), and 6 times in the high RB condition (n=27; 22% rate). The 8th category (brake tap, reposition to accelerator, then brake press) only appeared in the high level of RB condition and appeared 9 times (n=27; 33% rate). Both this behavior and the "wagging foot" behavior are similar because both foot behaviors occur between accelerator release and brake press. This implies that the drivers recognized the vehicle was actively braking in this time period, and this may have caused some uncertainty in what to do next. This also may be attributed to the fact that the drivers were novices and were not fully accustomed to RB. Perhaps the braking rate was higher than expected, which caused drivers to either wag their foot toward the brake (category 5) or go back and tap the accelerator (category 8).

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