Regenerative Braking

SAFETY RESEARCH USING SIMULATION
UNIVERSITY TRANSPORTATION CENTER

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Table of Contents

List of Figures

List of Tables

Abstract

A central question not yet examined in the literature is whether regenerative braking provides a kinematic negative acceleration advantage in time and distance over traditional driver accelerator release and service braking. This research explores three conditions of braking (traditional service braking, a low level of regenerative braking, and a high level of regenerative braking) to determine any safety advantages regenerative braking may offer. Thirty participants took part in a simulator study with a between-subjects study design, allocating 10 participants per condition. The study drive took place in a simulator and involved three braking events. The results showed a significant difference between the means of the three conditions for average acceleration of the vehicle in the time interval between the driver releasing the accelerator and pressing the brake for all three events. When events 1 and 2 were combined, there was significance with the same variable, as well as with maximum brake force. The significant measure, which compared the three means of the average acceleration of the vehicle in the time interval between throttle release and brake press, did indicate an acceleration advantage that was imparted to the driver. However, this advantage was not observed to propagate into traditional safety measures such as minimum TTC.

1 Overview

1.1 Background

In a vehicle powered by internal combustion (IC), there is a significant energy loss when the driver presses the brake pedal. When the brake pads pinch the rotors, friction is created and used to slow the vehicle. This friction turns the kinetic energy into heat, which is then lost and cannot be used by the vehicle. This is the traditional form of braking, known as service braking (SB).

Regenerative braking (RB) is a system that does not use the service brakes of the vehicle. It is typically used in electric vehicles to recapture the kinetic energy that would normally be lost while braking using the service brakes. Electric vehicles don't have a transmission and instead use a combination of RB and SB. When the driver releases the accelerator pedal, the vehicle immediately begins to slow down. Regenerative braking works by running the motor as a generator, allowing braking torque to slow the vehicle while generating electricity [14].

Regenerative braking has the potential to save from 8% to as much as 25% of the total energy use of the vehicle [14]. The technical implementation of RB varies; the system can be triggered via accelerator pedal or brake pedal or both pedals [5]. In the case of Tesla vehicles, the RB system is triggered as soon as pressure starts to be released from the accelerator pedal.

In braking events specifically, driver response time is not the only factor at play. First, in order to perceive that a slower vehicle ahead is an imminent hazard, there must be a measurable expansion of the visual angle of the lead vehicle. This is called the looming threshold, which at the lower end is approximately 0.003 rad/sec [9]. The time it takes for the driver to move their foot to the brake (response time) must also be added in. With IC-powered vehicles with modern automatic transmissions, when the driver releases the accelerator pedal, the vehicle essentially coasts until the brake pedal that engages the service brakes is pressed. With RB, simply lifting the foot begins the braking process.

1.2 Literature Review

Since Toyota first introduced RB in the Prius, which became the first commercialized vehicle to use RB, there has been a paucity of literature on the human factors and safety implications of this braking type. Previous research looked at making more efficient and effective RB systems but did not investigate the safety implications—either positive or negative [4, 14]. Safety implications include how RB may affect time to collision and the negative acceleration of the vehicle. As RB becomes more popular, there is an opportunity to examine how this new braking mechanism effects the performance of the vehicle.

1.3 Research Questions and Hypotheses

A central question not yet examined in the literature is whether RB provides a kinematic negative acceleration advantage in time and distance over traditional driver accelerator release and SB. In addition, since there are different levels of default RB, it is important to compare traditional SB to multiple levels of RB. Theoretically, RB should provide a braking advantage over SB because the braking process begins as soon as the driver releases the accelerator pedal, rather than when the driver presses the brake. This research explores this difference to determine any advantages that RB may have over SB.

2 Methods

2.1 Equipment

2.1.1 Simulator

The National Advanced Driving Simulator NADS-1 (Figure 2.1) was used for this study. The NADS-1 utilizes an actual vehicle cab and projects scenery 360 degrees around the driver on the interior walls of the dome that houses the cab. The vehicle cab is mounted on four independent actuators that provide vibration associated with driving on varying road surfaces. The entire dome is mounted on a motion base that can independently provide surge, sway, heave, roll, pitch, and yaw cues to the driver. The NADS-1 has a 13 degree-of-freedom large excursion motion base that can move around a space with a dimension of 20 x 20 meters and generate accelerations up to 0.6 G. The vehicle dynamics were based on the Oldsmobile Intrigue, while RB was modeled from data collected from the NADS Tesla Model S75D research vehicle.

Figure 2.1 – NADS-1 simulator

The NADS-1 features a full 2014 Toyota Camry cab inside the dome. It has a programmable center console screen that can display what is needed for the research study. Figure 2.2.2 shows what was displayed on the center console screen for this research study; it will be explained in detail later in the report.

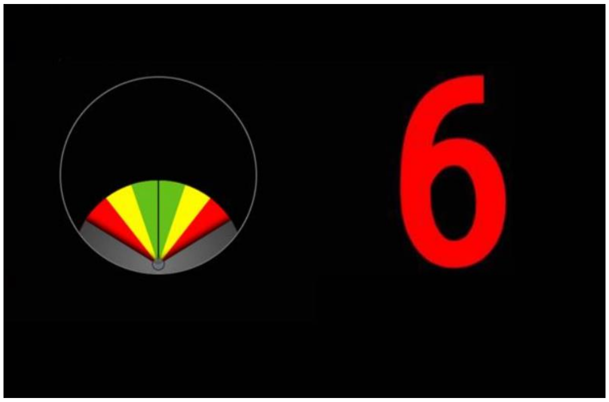

Figure 2.2 – Center console screen

This study did not provide any extra warnings or assistance to the drivers. In past research, systems such as brake pulse [6], collision warnings [7], and automatic emergency braking systems [4] were used to aid drivers to prevent collisions. This study did not use any of these systems, so all the responsibility fell on the driver.

2.2 Study Design

2.2.1 Participants

For this study, 30 participants between the ages of 21 and 45 years split by gender drove in the NADS-1 driving simulator. All were required to have an active driver's license. Participants were compensated $15 for their participation in the 45-minute study. If the study took longer, participants were compensated accordingly.

Participants drove either a vehicle (simulated) with SB, a Tesla with the lower level of RB (.02 to .05 g), or a Tesla with the higher level of RB (.15 to .2 g).

The NADS participant registry, which contains over 5,000 individuals, was queried for participants between 21 and 45 years old, and an email was sent to those who had provided an email address. Potential participants in the registry were also contacted by telephone. A telephone screening procedure was used to ensure participants met all inclusion requirements. Participants who met all requirements and could meet the study schedule were scheduled for study participation [2].

2.2.2 Study Design

In order to answer the central research question, the study compared three braking conditions: SB, Tesla RB low, and Tesla RB high. The low level of RB slowed the car at approximately .02 to .05 g, while the high level slowed the vehicle at approximately .15 to .2 g. Participants were randomly assigned to one of the three experimental groups. Each group represented a braking condition.

2.2.3 Number Recall Task

A distraction task using number recall was used during the drive. A monitor was placed in the center stack area of the instrument panel. The number recall task was adapted from the Crash Warning Interface Metrics projects [2]. In that study, the screen for the number recall task was mounted on the front of the passenger seat headrest [2]. This research placed the monitor in the center stack area of the instrument panel, so that the driver did not have to turn their head as much and could use periphery vision while engaging in the task, thus making it a milder task. The distraction was used for both mild events to prevent the driver from picking up cues that a braking event may occur, but it was not used for the severe event because there were no visual cues that a braking event was about to occur. The number recall task also occurred throughout the drive so the participant stayed engaged and could not use the task to predict an event. The task occurred at a rate of about once per minute.

The driver was notified of the number recall task via a chime. About a second after the chime, five random single-digit numbers were presented one at a time on the center console, approximately a half second apart. After all five numbers were presented, the participants had to recall all of the numbers out loud in the correct order. If the participant was unsure, they had to make their best guess. The researchers in the control room and the simulator made sure the participant was engaging in the task every time.

2.2.4 Speed Task

For the entire length of the drive, participants were instructed to drive 55 mph. In order to assist them in this speed task, on the center console screen to the left of the number recall task a dial was placed (fig. 2.2). The dial was placed on the center console screen so that even during the number recall task, participants would have a reference allowing them to easily know what their speed was. If the needle was in the green area, then there speed was acceptable. Too far to the right their speed was too fast, and too far to the left their speed was to slow.

2.2.5 The simulated drive

This study had three separate braking events: two mild and one severe. For all events, the initial speed of the lead vehicle was 55 mph. In the first event, the lead vehicle's average minimum negative acceleration was -.95 g and the average minimum speed was 19.03 mph. In the second event, the lead vehicle's average minimum negative acceleration was -.85 g and the average minimum speed was 23.67 mph. In the final event, the lead vehicle's average minimum negative acceleration was only -.61 g, but the average minimum speed was 0. What made the final event severe was the fact that the lead vehicle came to a complete stop. This forced the participant driver to also come to a complete stop, whereas for the first two events, the participant driver did not have to come to a complete stop.

The simulated drive began with the participant vehicle at a standstill. In front of the participant vehicle were two lead vehicles, both with a fixed headway gap. The two lead vehicles immediately began driving at a set speed until the driver exceeded 20 mph, at which time the lead vehicles changed to a maintain-gap behavior. The participant had to accelerate to 55 mph and remain at this speed throughout the drive. The time between the start and the first event gave the participant more than enough time to get up to speed without the lead vehicles getting too far ahead.

The first event began with a number recall task for the participant to complete. During this task, the vehicle in front of the lead vehicle turned right onto another road, causing the lead vehicle to slow down. This was the first mild event. Following the event, there was just one lead vehicle in front of the participant vehicle, and it remained there for the rest of the drive. After each event, the participant was expected to accelerate to 55 mph.

The second event began with a number recall task for the participant to complete. During this task the lead vehicle braked because of a deer on the side of the road. This was the second and final mild braking event. Following the event, the participant was expected to accelerate to 55 mph.

The final braking event did not have a number recall task. The computer-simulated car slowed rapidly for no apparent reason until it came to a complete stop. This was the final and most severe event. Once the participant vehicle came to a complete stop, the drive was over.

2.2.6 Dependent Measures

This study used measures to explore all possible advantages and disadvantages that RB might have when compared to SB.

The first measure was crash or no crash. This is binary and only looks at whether a collision was made between the two vehicles. A crash would indicate that there was a failure with either the system or the person.

Another measure was time to collision (TTC). Time to collision looks at how much time the participant vehicle has at a certain moment before it collides with the vehicle in front of it. This was measured three ways: TTC at throttle release, TTC at the first brake press, and minimum TTC in the event.

The third measure was the time it took to begin the braking process. Figure 2.3 shows the timeline of the braking process. When time equals t0, the lead vehicle’s brake lights come on. At time t1, the participant releases the accelerator, and at time t2, the participant presses the brake pedal. The time to begin the braking process was measured using three equations: from time t0 to time t1, time t0 to time t2, and time t1 to time t2.

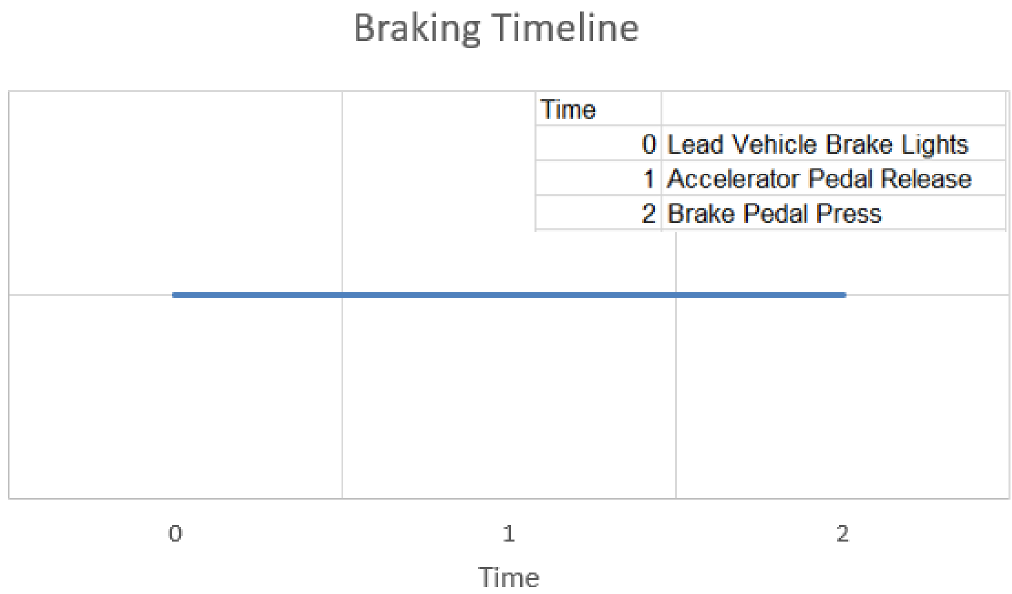

Figure 2.3 - Driver behavior braking timeline

The fourth measure was distance traveled during the braking event. This is measured from the moment the lead vehicle's brake lights come on until the participant vehicle begins to increase speed after slowing down.

The fifth measure was maximum brake pedal force. Maximum pedal force is related to vehicle deceleration in the sense that more force means higher deceleration. This is measured in pound force (lbf).

The sixth measure was brake time. This is measured three ways. The first is from the time of the initial brake press, t2, to the time the driver takes their foot off the brake pedal (t3). The second is from the time of the accelerator release (t1) to the time of the brake release (t3). The third is the total brake time, which is measured from the time of the lead vehicle brake lights turning on, t0, to the time the driver releases the brake pedal, t3.

The seventh measure looked at the negative acceleration of the vehicle. This measure explored average negative acceleration during the entire brake time, and the average acceleration of the vehicle from the time the driver removes their foot from the accelerator, t1, to the time the driver presses the brake, t2.

2.3 Procedure

2.3.1 Before the Drive

Upon arrival at the NADS facility, participants were escorted to a briefing room where the informed consent document was reviewed with participants. Once informed consent was obtained, their licenses were confirmed as valid, and a video release form and a payment form were completed. Driving history and demographic data were collected. Participants then watched a self-paced PowerPoint presentation describing the driving simulator and the task they were expected to perform while driving. They then practiced the distraction task [2].

2.3.2 During the Simulated Drive

During the drive, there was an experimenter in the back seat of the vehicle cab and a researcher in the control room monitoring the safety of the drive.

The participants engaged in five minutes of driving with the simulator before the study began so they could get used to the simulator and the style of braking. Although no specific time has been established as a proper warm-up, literature shows that most warm-ups are around five minutes [10]. Five minutes was enough time for the participant to locate all the necessary controls and screens and adjust to the feel of the style of braking they were using.

To ensure consistency in the speed of the vehicles, participants had to follow the speed limit of 55 mph as closely as possible.

After the five-minute warmup, the study began. Each trial included all three braking events and took about ten minutes to complete. The distance traveled was approximately 8.3 miles.

During both the warmup and the study drive, the participants were required to engage in a number recall task. If the participant did not engage or was completing the task incorrectly, the researcher would correct them during the practice drive.

2.3.3 After the Drive

Following the study, participants were debriefed. Their compensation was reviewed, and any questions were answered prior to the conclusion of their study visit. Each participant was also provided a debriefing statement that explained the true purpose of the study and asked not to discuss the details of the study until after all data collections for the project were concluded [2].

3 Results

The Kruskal Wallis test was used to compare means between levels of RB because the residuals from an ANOVA were not normally distributed, and a nonparametric test was needed to determine whether there were statistically significant differences among the three groups. The confidence interval used to determine significance was 95% for all tests. This testing was done through IBM SPSS.

Table 3.1 - Significant Results of the Kruskal Wallis Test

Event Measure	Value	1	2	3	1 and 2 combined
Average acceleration of vehicle in the time interval between when the driver releases the accelerator and presses the brake	Kruskal-Wallis H DF Asym. Sig.	16.175 2 0.000	8.932 2 0.011	15.283 2 0.000	11.097 2 0.004
Maximum brake force during braking event	Kruskal-Wallis H	-	-	-	7.177

	DF	-	-	-	2
	Asym. Sig	-	-	-	0.028

The output values are Kruskal-Wallis H, degrees of freedom (DF), and asymptotic significance. Kruskal-Wallis H is the chi-squared statistic. Degrees of freedom are 2 for every output because each output compares the means for 3 levels of RB, and degrees of freedom are measured as n-1. 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.

Columns 3, 4, and 5 of **Error! Reference source not found.** show the output for all significant values from the Kruskal Wallis test for events 1, 2, and 3. For this analysis, all three events were tested separately, and within each event the three levels of braking were compared. For all three events, the only measure with asymptotic significance was average acceleration of the vehicle in the time interval between accelerator release and brake press. This means that when comparing the three levels of braking, only average negative acceleration of the vehicle in the time interval between accelerator release and brake press showed a difference among the three means.

The last column in **Error! Reference source not found.** shows the output for the Kruskal Wallis test when the first two events were combined as one event. In order to combine the two events, the average value for each variable in the two events was taken. The two variables with asymptotic significance were (1) average acceleration of the vehicle in the time interval between accelerator release and brake press, and (2) maximum brake force.

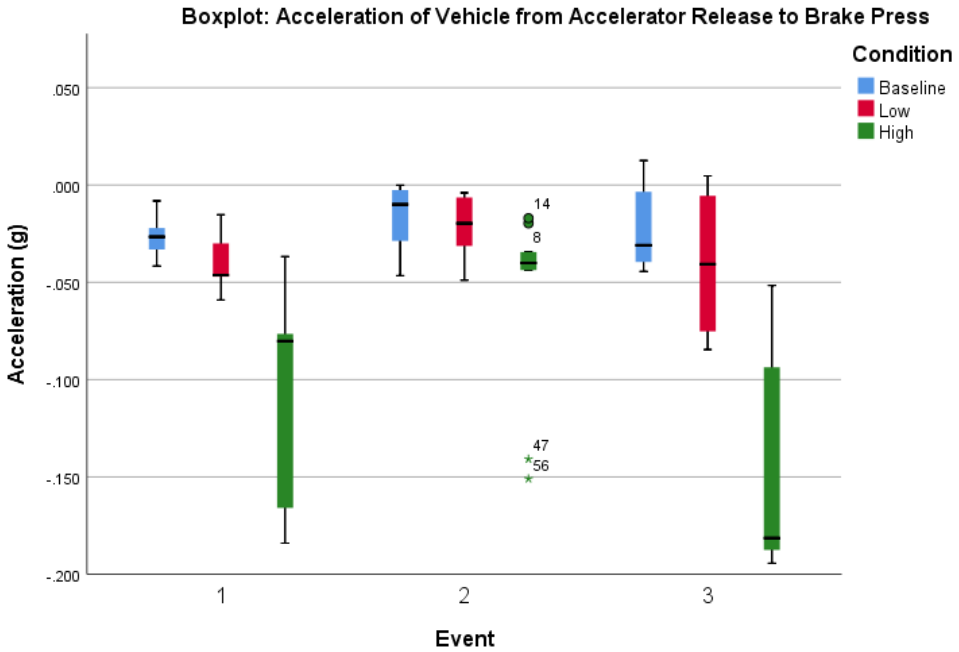

Figure 3.1 - Average negative acceleration in g boxplot (time interval of accelerator release to brake press)

Figure 3.1.1 shows boxplots of the average negative acceleration for each event. The average acceleration of the vehicle in the time interval between accelerator release and brake press shows there is little difference between baseline and low, but the high level of RB shows a significant difference. There is also much more variance when it comes to the high level of RB.

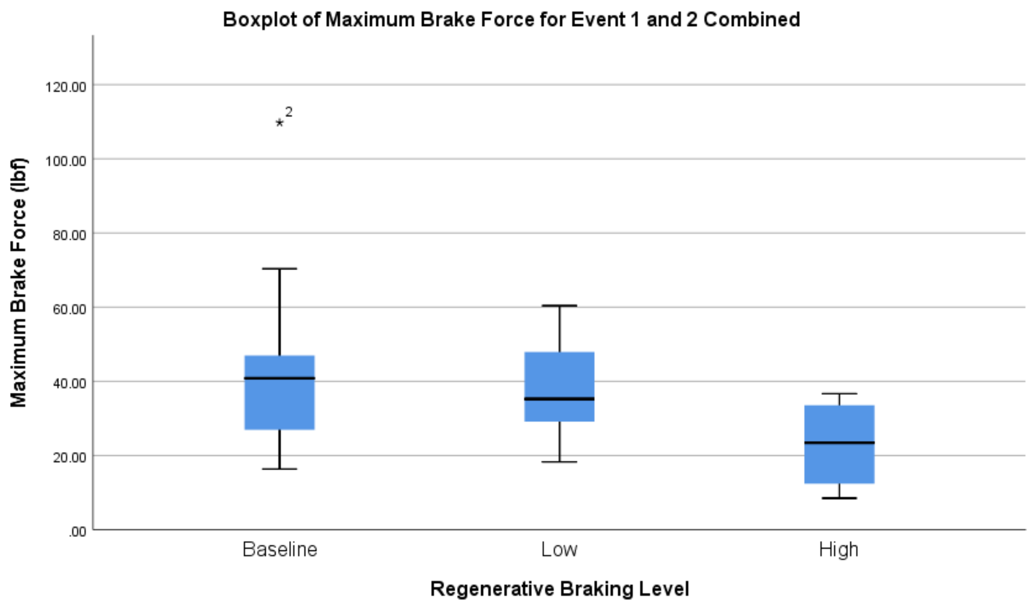

Figure 3.2 - Boxplot of maximum brake force (events 1 and 2 combined)

Figure 3.2.2 shows three boxplots for the combination of events 1 and 2 for maximum brake force at the three levels of RB. There is not a statistically significant difference between the baseline condition and the low level of regenerative braking. The high level of regenerative braking shows that the drivers had a lower maximum brake force when they were part of the high RB condition.

4 Conclusion

Since the braking process begins earlier with RB than traditional SB, RB should provide a negative acceleration advantage in time and distance over SB. The significant measure, which compared the three means of the average acceleration of the vehicle in the time interval between throttle release and brake press, did indicate an acceleration advantage that was imparted to the driver. However, this advantage was not observed to propagate into traditional safety measures such as minimum TTC.

When events 1 and 2 were combined and maximum brake force showed a significant difference in means between one of the three conditions, this gave insight into how RB was being used. While maximum brake force showed a statistically significant difference, measures such as average acceleration and TTC were found to not be statistically significantly different. The participants were able to properly gauge the assistance that RB was providing and therefore did not have to press on the brake pedal as hard because RB was giving them an advantage in the braking process. With just a five-minute warmup, participants were able to adjust how they typically braked and incorporate RB into their braking strategies. This also gives insight into what people use in their perception in order to brake. People rely more on visual cues such as looming cues and TTC than on brake pedal force.

The next steps are to explore the decomposition of driver response in electric vehicles with RB and to explore the possibility of implementing dynamic RB. Dynamic RB could alter how quickly RB slows the vehicle depending on the environment around the vehicle. Regenerative braking would likely change in situations that require quick braking but not automatic emergency braking.

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Appendix A: Detailed Statistical Results

Table A.1 - Event 1 Kruskal-Wallis Results

Variable	Event	Kruskal-Wallis H	df	Asymptotic Significance
TTC at Throttle Release	1	2.945	2	.229
TTC at brake press	1	.797	2	.671
Minimum TTC	1	1.030	2	.598
Number of collisions	1	.000	2	1.000
Lead vehicle brake lights to driver throttle release	1	2.095	2	.351
Lead vehicle brake lights to driver brake press	1	.279	2	.870
Driver throttle release to brake press	1	1.533	2	.465
Driver brake press to brake release	1	.844	2	.656
Driver throttle release to brake press	1	1.757	2	.415
Lead vehicle brake lights to driver brake release	1	1.116	2	.572
Average vehicle acceleration	1	4.446	2	.108
Average acceleration (T1 to T2)	1	16.175	2	.000
Distance travelled	1	2.240	2	.326
Maximum brake force	1	4.831	2	.089
Minimum distance to lead vehicle	1	2.510	2	.285

Table A.2 - Event 2 Kruskal-Wallis Results

Variable	Event	Kruskal-Wallis H	df	Asymptotic Significance
TTC at Throttle Release	2	1.055	2	.590
TTC at brake press	2	1.752	2	.416
Minimum TTC	2	.699	2	.705
Number of collisions	2	.000	2	1.000
Lead vehicle brake lights to driver throttle release	2	2.181	2	.336
Lead vehicle brake lights to driver brake press	2	1.745	2	.418
Driver throttle release to brake press	2	1.712	2	.425
Driver brake press to brake release	2	2.413	2	.299
Driver throttle release to brake press	2	2.181	2	.336
Lead vehicle brake lights to driver brake release	2	2.109	2	.348
Average vehicle acceleration	2	3.375	2	.185
Average acceleration (T1 to T2)	2	8.932	2	.011
Distance travelled	2	1.210	2	.546
Maximum brake force	2	4.965	2	.084
Minimum distance to lead vehicle	2	.777	2	.678

Table A.3 - Event 3 Kruskal-Wallis Results

Variable	Event	Kruskal-Wallis H	df	Asymptotic Significance
TTC at Throttle Release	3	2.092	2	.351
TTC at brake press	3	.627	2	.731
Minimum TTC	3	.010	2	.995
Number of collisions	3	.000	2	1.000
Lead vehicle brake lights to driver throttle release	3	.666	2	.717
Lead vehicle brake lights to driver brake press	3	1.170	2	.557
Driver throttle release to brake press	3	1.425	2	.490
Driver brake press to brake release	3	.260	2	.878
Driver throttle release to brake press	3	.837	2	.658
Lead vehicle brake lights to driver brake release	3	.494	2	.781
Average vehicle acceleration	3	.421	2	.810
Average acceleration (T1 to T2)	3	15.283	2	.000
Distance travelled	3	3.688	2	.158
Maximum brake force	3	1.695	2	.428
Minimum distance to lead vehicle	3	.162	2	.922

Table A.4 - Event 1 and 2 Kruskal-Wallis Results

Variable	Event	Kruskal-Wallis H	df	Asymptotic Significance
TTC at Throttle Release	1 and 2	3.270	2	.195
TTC at brake press	1 and 2	.947	2	.623
Minimum TTC	1 and 2	1.745	2	.418
Number of collisions	1 and 2	.000	2	1.000
Lead vehicle brake lights to driver throttle release	1 and 2	2.682	2	.262
Lead vehicle brake lights to driver brake press	1 and 2	.948	2	.623
Driver throttle release to brake press	1 and 2	2.002	2	.367
Driver brake press to brake release	1 and 2	1.093	2	.579
Driver throttle release to brake press	1 and 2	.525	2	.769
Lead vehicle brake lights to driver brake release	1 and 2	.179	2	.915
Average vehicle acceleration	1 and 2	4.663	2	.097
Average acceleration (T1 to T2)	1 and 2	11.097	2	.004
Distance travelled	1 and 2	.258	2	.879
Maximum brake force	1 and 2	7.177	2	.028
Minimum distance to lead vehicle	1 and 2	2.914	2	.233