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Evaluation of a Novel Emergency Braking Task on a Driving Simulator with Haptic Anti-Lock Braking System Feedback

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Abstract: Rear-end crashes are one of the leading types of crashes today. The anti-lock braking system (ABS) was designed to assist drivers during emergency braking situations by preventing wheel lock up, allowing drivers to retain control of the vehicle. Not all drivers have knowledge and experience with ABS, especially the haptic brake pedal feedback produced by ABS. There studies introduce a new method to train ABS using an emergency braking task on a simulator and an interactive exercise, *Pedals Emergency Stop*©. The interactive exercise was designed to prompt participants to press the brake pedal in a motion that is consistent with emergency braking and experience haptic ABS feedback. Participants that depressed the brake pedal quickly to the maximum travel and held that pedal position "passed" the trial. In Study 1, participants (N = 63) completed 15 trials, where it took on average three trials to "pass" for the first time, and 85% of the participants experienced their first "pass" within the first four trials. There were no differences observed between participants with previous knowledge and experience feeling ABS versus those who did not have prior knowledge and experience with ABS. The participants in this study thought that they had enough trials, that the exercise was a practical tool, and recommended the task for new drivers and refresher training, as well as for evaluating fitness to drive. Suggested improvements included a practice followed by three tests, all with four trials each; passing criteria of three out of four trials; and modifications to the feedback presented immediately after completing each trail. Study 2 was conducted (N = 38) to investigate the proposed "passing" criteria, where 95% passed on Test 1. The results revealed that the criteria to pass was reasonable. Future research should examine how the *Pedals Emergency Stop*© interactive exercise generalizes to on-road driving.

Keywords: adult drivers; emergency braking training; braking performance; anti-lock; braking system training; simulation

Citation: Mims, L.; Brooks, J.; Gangadharaiah, R.; Jenkins, C.; Isley, D.; Melnrick, K. Evaluation of a Novel Emergency Braking Task on a Driving Simulator with Haptic Anti-Lock Braking System Feedback. *Safety* **2022**, *8*, 57. https://doi.org/10.3390/safety8030057

Academic Editor: Garrett Mattos

Received: 3 June 2022
Accepted: 3 August 2022
Published: 5 August 2022

This introduction aims to provide an overview of the anti-lock braking system (ABS), as well as relevant research on existing training methods previously explored. Then, it summarizes findings from the Light Vehicle ABS Research Program, focused on preferred methods of ABS training, as well as the limited research on the use of driving simulators and ABS. Finally, the introduction concludes with the use of driving simulators for driver training for new drivers, as well as driver rehabilitation.

1. Introduction

Rear-end crashes are one of the most common types of crashes in the US [1,2]. Prior to anti-lock braking systems (ABS), a vehicle's wheels could "lock up", which could cause the loss of steering control. As a result, stopping distances were longer than vehicles which offer ABS [3]. ABS quickly holds and releases the brakes to prevent the wheels from locking, which creates haptic feedback in the brake pedal [3,4]. To activate ABS, the driver must slam on the brake pedal to fully depress the pedal, then maintain brake pedal pressure until the vehicle comes to a complete stop.

ABS became more common on passenger vehicles in the mid to late 1990s [5]. Then, the National Highway Traffic Safety Administration (NHTSA) began comparing the crash data between vehicles equipped with ABS and vehicles with conventional brakes (non-ABS) to determine if ABS impacted crashes rates. During multiple investigations, ABS demonstrated benefits, such as reductions in multiple vehicle crashes, but also showed increases in single vehicle crashes involving a vehicle running off the road to lead in an impact with an object or rollover [6]. To help drivers increase performance during emergency braking while activating ABS, multiple researchers and government agencies have explored various training methods.

1.1. ABS Training

Mollenhauer, Dingus, Carney, Hankey, and Jahns [7] investigated the use of a low-cost training method, a pamphlet that explained the correct ABS activation technique. Twenty-seven drivers ranging in age from 20 to 26 years with no previous ABS experience were divided into two groups; one group read the pamphlet and the control group did not prior to completing braking tasks on a track which was covered in a quarter inch of ice. First, the participants were asked to stop the car as quickly as possible while traveling straight without steering input (straight-line braking) at 25 mph. Second, braking was evaluated while driving around a curve at 20 mph. Third was the surprise event condition, which used a Styrofoam block that suddenly emerged into the driver's lane while exiting the track. The results showed that the drivers who read the pamphlet used the correct braking technique and stopped an average of 35 feet sooner than participants who did not review the pamphlet during the straight-line braking event. There were no differences between the groups in either the curved braking or surprise braking events.

Petersen, Barrett, and Morrison [8] examined braking performance after 26 participants (with an average age of 27.9 years and 9.2 years of driving experience) completed a two-day post-license training program. The control group had an average age of 31.7 and 14.2 years of driving experience. During the program, participants were taught a two-phase braking technique, where the driver first depressed the pedal quickly near the maximum travel, then, for the remaining distance of pedal travel, the driver applied pressure steadily until the pedal was fully depressed. The two-phase technique was taught because it could be used in vehicles with and without ABS. All participants performed straight-line emergency brake tests at 50 mph and 62 mph on a track. The results concluded that the drivers who completed the program did not rely on ABS; while these drivers had smooth braking profiles, they stopped an average of one car length further, past the location of the group that did not participate in the training program.

There are many post-license advanced driver training classes offered to teen and adult drivers that provide an overview of ABS and include training on activating ABS. Examples of post-license driver training programs are the half day Guard Your Life Challenge (GYL) for teens and the full day Car Control Classes (CCC) for teens and adults, both of which utilize the same closed road track and some of the same exercises [9,10]. During the GYL and the CCC, drivers attempt to activate ABS by speeding up to the instructor's designated speed and then slamming on the brakes at a designated set of cones. The drivers' first run of the exercise is at approximately 30 mph and the speed steadily increases with each subsequent run up to 60 mph, over approximately seven runs. After each run, drivers received feedback on their performance from a professional driving instructor.

A survey was completed by 134 teens after the GYL program, and 50 of those teens participated in a follow-up phone interview three months later [9]. The results from the phone interview showed that during that time span, 72% of the participants reported using the skills they learned while driving since the program. A surprising 69% reported using knowledge gained from the program to avoid a crash, with ABS being the most common skill used (36%). This suggests that the teens benefited from practicing ABS activation.

A second study [11] investigated parents' views of the GYL program. Surveys were completed by 134 parents regarding their own experiences with ABS. A total of 85% of parents reported using ABS and 31% reported completing ABS training. Interestingly, 53% of the parents reported teaching their teen about ABS, with 87% discussing ABS and only 13% providing hands-on experience [11]. While the majority of parents reported experiencing ABS themselves, only a small percentage of parents provided hands-on ABS experience for their teens, suggesting that ABS training is worthy of further investigation.

The CCC, offered to both teens and adults, is more involved than the half day GYL. The CCC includes a full day of defensive driving with additional exercises, which includes the ABS exercise. A total of 177 adults completed a survey after the CCC class, with 64 participating in a follow-up phone interview six months later [10]. During the phone interview, 77% of the adults reported using skills from the CCC on the road since the class and 22% reported using ABS. Of the adults that reported using skills from the CCC on the road, 23% reported using the skills to avoid a crash; 85% of those who used their new skills to avoid a crash reported using ABS. The results of the phone interview with the adults are consistent with the interview results from the teens from the GYL program [9], where ABS was reported as the most used skill to avoid a crash. The results of this study suggest that many adults did not understand or have experience activating ABS prior to the CCC [10].

The focus of the next study investigated how drivers' knowledge and experience with ABS prior to the CCC affected their performance when activating ABS during the on-track exercise [12]. A total of 79 participants ranging from 18 to 78 years of age completed a survey prior to the class to quantify their background knowledge of and experience activating ABS. During the ABS exercise, instructors rated participants' performance using a behaviorally anchored ratings scale, which was developed collaboratively with the professional driving instructors. The scale uses a five-point rating, where a rating of 1 corresponds to no ABS activation and a rating of 5 indicates full ABS activation during the entire stop.

The results of the study showed that the participants who had (1) previous knowledge of what ABS felt like when activated; (2) experienced additional driver's training (beyond driver's education) with or without ABS experience; and/or (3) practiced activating ABS prior to the CCC had significantly higher ratings during the first run of the ABS exercise. Sixty percent of the participants were able to activate ABS during the first run of the exercise. All but one of the participants were able to achieve a rating of 5, fully activating ABS at least once during their seven runs. The most common feedback that participants received if they did not receive a rating of 5 was to "press the brake pedal and keep it pressed until the vehicle comes to a complete stop" (26%); "look where you want the vehicle to go" (25%); "press the brake harder or as hard as you can" (23%); or "slam the brake pedal from the start instead of easing onto it" (14%). The outcome of this study suggests that knowledge and experience with ABS influences drivers' ability to activate ABS, as well as providing guidelines for ABS feedback [12].

1.2. NHTSA Light Vehicle ABS Research Program

NHTSA created the Light Vehicle ABS Research Program to investigate why the inclusion of ABS on vehicles resulted in increases in run-off-road crashes. The ABS Research Program consisted of multiple research tasks, and two of the tasks within the program were related to driver training.

In Task 5.2/5.3, NHTSA explored the inclusion of a video on ABS operation and use (GM video for new vehicle buyers; [13]) on collision avoidance behavior for 82 of the larger studies with 246 total participants [14]. The participants drove on a closed road track through an intersection four times. During the fourth run, the participants experienced a crash-imminent scenario where a model vehicle (a fake vehicle that would not cause injury to the driver if a crash occurred) came 6 feet into the participant's lane unexpectedly, causing the participant to make an emergency maneuver to attempt to avoid the model. The results showed no evidence that watching the video had any effect on crash avoidance behavior. Tasks 5.2/5.3 also explored braking practice before a crash-imminent scenario. Some of the participants had a braking practice on the track in slippery conditions prior to the study. During the practice, the participants drove towards a cone in the center of their lane. They were told to avoid the cone while approaching it, but were not given any instructions on how to avoid the cone or how to activate ABS. The session was intended to allow participants to experience ABS before the study. Since the participants were not given instructions during the braking practice to activate ABS, nor was their performance during the practice reported, it is unknown if the participants activated ABS. The braking practice did not have any effect on participants' crash avoidance behavior during the study [14].

NHTSA used the National Advanced Driving Simulator (NADS) in Task 5.1 [15], which investigated crash avoidance behavior, like Task 5.2/5.3. NADS uses a six-degrees-of-freedom base and fully instrumented Saturn with a 190-degree forward and 60-degree rear field-of-view, retrofitted with ABS, and utilizes a full vehicle dynamics model [15]. The simulator was used to explore the collision avoidance behaviors of drivers, rather than exploring ABS training.

1.3. Simulators for Driver Training

Simulators provide a safe environment to explore and train driving behavior. They offer the ability to create a repeatable, controlled driving task, which is ideal for training purposes. Simulators are used as a clinical assessment and rehabilitation tool [16]. Compared to the variability that exists in on-road settings, simulators can be used to systematically detect impairments and/or errors with at-risk drivers [17]. The U.S. Department of Veterans Affairs driver rehabilitation program utilizes driving simulators as an evaluation and training tool for veterans [18]. Simulators are also used to train new drivers, including at-risk driver populations, who can become overwhelmed when learning how to operate a vehicle. Therefore, Brooks, Mossey, Tyler, and Collins [19] suggest the use of interactive exercises that allow drivers to practice focusing on one aspect of driving, such as turning the steering wheel or operating the pedals, prior to scenarios with a roadway scene. Brooks et al. [20] developed and explored the use of interactive exercises, consisting of the visual representation of a steering wheel, gas and brake pedals, or a stoplight. Brooks et al. [20] demonstrated that the interactive exercises were an effective training tool for both young neurotypical drivers, as well as teens with intellectual disabilities. When using simulators, simulator sickness must be considered, especially with roadway scenes that include turns and abrupt braking events [21]. Simulator sickness encompasses many factors, but one of the most prominent is visual immersion, especially with more immersive simulators [20]. A benefit of interactive exercises is that simulator sickness is not possible since a roadway scene is not used.

2. Research Aims

This manuscript includes two studies focused on the development and evaluation of a driving simulator and interactive exercise for an emergency braking task with haptic ABS feedback. The simulator and interactive exercise aim to provide a safe and repeatable environment. The interactive exercise, *Pedals Emergency Stop*©, utilizes images of pedals instead of a driving scene to prevent simulator sickness, since driving scenarios with abrupt stopping are known to be triggers of simulator sickness. The first study aims to investigate the novel simulator task, the *Pedals Emergency Stop*© interactive exercise, while the second study aims to address the improvements identified from Study I, including the passing criteria.

3. Study I

This study investigated participants' performance during an emergency braking task using a custom driving simulator with haptic ABS brake pedal feedback and the *Pedals Emergency Stop*© interactive exercise. The study determined if there were differences between drivers with and without prior ABS experience, as well as if differences exist based upon when the description of emergency braking with ABS is introduced.

3.1. Materials and Methods

3.1.1. Participants

Sixty-three participants with a valid license were recruited to participate in the study. Two participants were dropped due to left foot braking. Of the remaining 61 participants, there were 30 males and 31 females, who ranged from 18 to 60 years of age with an average age of 35.8 years (*SD* = 11.6 years). The participants were grouped by their knowledge and experience using ABS, where if a potential participant was able to describe the haptic feedback associated with ABS activation, they were in the prior ABS experience group. If potential participants did not report previously activating ABS or who provided an inaccurate description of haptic feedback, they were in the group without knowledge and experience activating ABS. Then, participants were grouped a second time by when they received the description of emergency braking, where half received the description before *Pedals Emergency Stop©* and the other half received the description after their first attempt. The four groups had 15 or 16 participants each (see Table 1). There were more females with no knowledge and experience feeling ABS; there were more males that had knowledge and experience feeling ABS.

Table 1. Participant groupings based on ABS experience and order of the description of emergency braking during the *Pedals Emergency Stop©* exercise.

ABS Grouping	**Order of Description of Emergency Braking during *Pedals Emergency Stop©***	
	Before	**After the First Attempt**
No knowledge and experience feeling ABS	16 participants 4 males, 12 females Avg. age 35.0 (std. dev. = 10.0)	15 participants 5 males, 10 females Avg. age 35.8 (std. dev. = 11.6)
Has knowledge and experience feeling ABS	15 participants 10 males, 5 females Avg. age 37.8 (std. dev. = 12.5)	15 participants 11 males, 4 females Avg. age 34.6 (std. dev. = 13.2)

3.1.2. Simulator

The simulator allowed participants to gain experience emergency braking and feel haptic feedback that is consistent with ABS activation and feedback in a vehicle. The simulator used a DriveSafety interactive exercise along with commercially available products to enable the desired ABS feedback (see Figure 1).

The Fanatec ClubSport V3 pedals set was utilized, where the brake pedal's adjustable damper was set to zero to allow the pedal to move freely [22]. The resistance of the pedal was verified by a subject matter expert. The pedal travel was set to allow for the maximum amount of pedal travel (1.75 in). The typical pedal travel of a brake pedal on a passenger vehicle is about 2 in (measured from a 2012 Toyota Camry and 2022 BMW 330i).

This task required the participants to slam the brake pedal. As a result of this slamming and the desire for a small footprint simulator, a chair was mounted to rails to prevent the participants from tipping back. The use of a chair led to a simulator layout based upon the packaging that was consistent with a pick-up truck (i.e., Ford F-150, Chevrolet Silverado 1500, etc.). The Fanatec CSL Elite Wheelbase was mounted to the side of the table since a steering wheel was not required for this task.

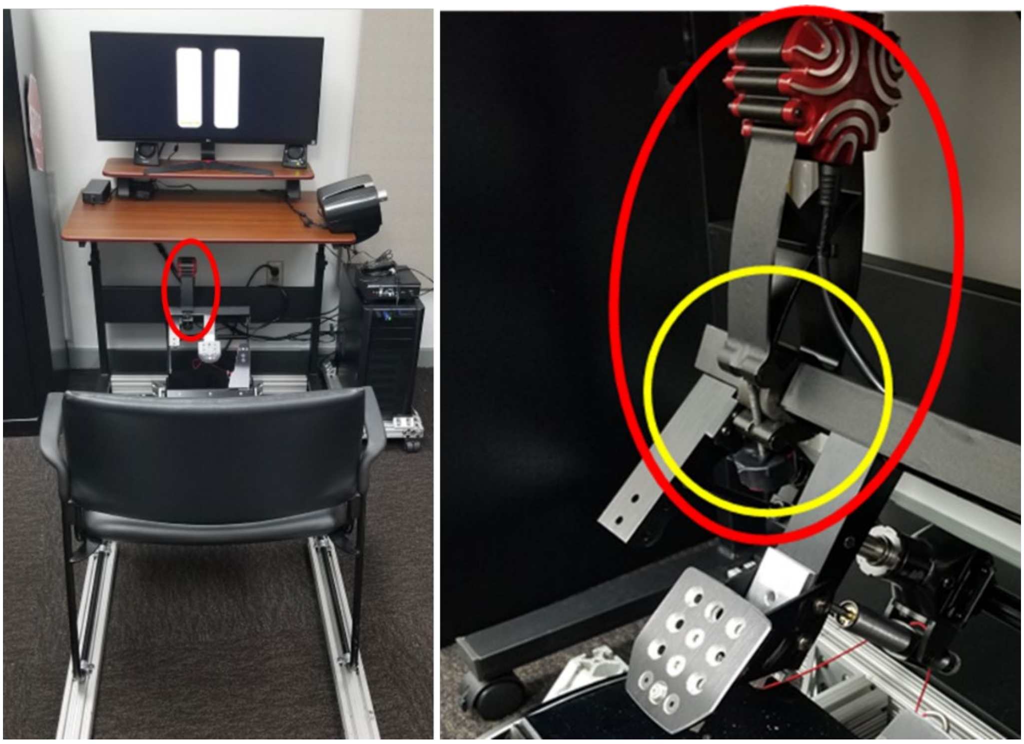

Figure 1. Simulator setup with device that delivers haptic ABS feedback circled in red (ButtKicker). The yellow circle highlights the attachment point to the pedal assembly.

ABS Haptic Brake Pedal Feedback

The haptic ABS feedback was delivered to pedals through a device called a ButtKicker Gamer2, which is typically used to provide haptic feedback to gamers by attaching the device to the base of an office chair. To simulate the brake pedal feedback associated with ABS activation, the ButtKicker Gamer2 was installed onto the Fanatec ClubSport's pedal assembly.

To simulate feedback from ABS through the ButtKicker, an audio file containing the vibration measured from a vehicle during ABS activation by a professional driver was used.

3.1.3. Interactive Exercises

DriveSafety's interactive exercises which focus on the gas and brake pedal tasks were used. Interactive exercises use symbols rather than a driving scene; therefore, simulator sickness was not possible.

Pedals Chase©

The *Pedals Chase©* interactive exercise uses dynamic targets on the visual representation of a gas and brake pedal (see Figure 2). The participant's goal is to keep the indicator in the target zone while the target zone moves up and down first on the gas pedal and then on the brake pedal. Level 2 of this interactive exercise was used, where the target zone is 25% of the size of the pedal. To "pass" this task and move on to the next task, the participant needed to make less than three errors (leaving the target zone).

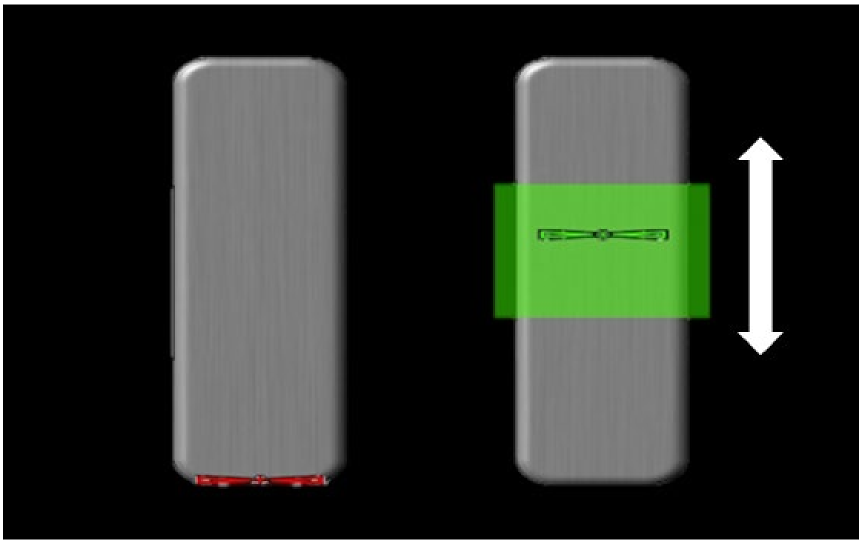

Figure 2. *Pedals Chase©* Level 2.

Pedals Emergency Stop©

The *Pedals Emergency Stop©* interactive exercise provides repetition with emergency braking with ABS haptic feedback. The interactive exercise looks identical to *Pedals Chase©* and begins with a moving target on the gas pedal (see Figure 3 left). After a randomized amount of time, a brake target zone appears on the very top of the brake pedal (see Figure 3 right) and a loud, audible "Stop" prompts the participant to place the indicator in the target zone on the brake pedal. The target zone is located at the very top of the brake pedal and extends beyond the brake to encourage participants to press the brake pedal to achieve the pedal's maximum travel.

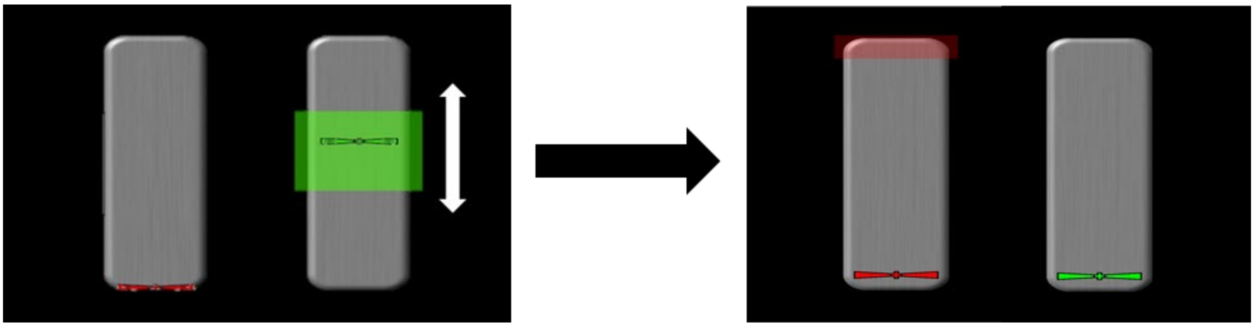

Figure 3. *Pedals Emergency Stop©* moving gas target (**left**) and brake target (**right**).

The goal for this task is to stomp on the brake pedal quickly and hold the indicator in the target zone for three seconds (or three tones). If the ABS is triggered, haptic feedback is provided. Holding the indicator in the target zone simulates the time it takes to brake quickly and bring a vehicle to a complete stop. In order to press the brake pedal quickly enough to activate ABS on the simulator or "pass", the time from pressing the brake until the indicator is in the target zone should be approximately less than 0.035 s, which was determined through information from NHTSA [23] and verified by a subject matter expert who was a professional driver. If the participant did not press the brake pedal within 0.035 s, the ABS feedback was not instant but delayed by one second, since the participant eased onto the brake pedal.

After each brake attempt, the results were displayed with the participant's performance for each attempt. If a participant either did not press the pedal fast enough to instantly trigger the haptic ABS feedback and/or did not hold the indicator in the target zone for three tones, the individual received a "no" in the middle "Pass?" column, along with advice to help improve their performance. If the participant did not press the pedal fast enough to instantly trigger the haptic ABS feedback, "Press harder and faster" was presented. If the participant did not hold the brake pedal in the target zone for three tones, "Hold longer" was presented. If the participant did not press the pedal fast enough and did not hold the indicator in the target zone for three seconds, "Press harder and faster" was presented. The advice from the *Pedals Emergency Stop©* interactive exercise was prioritized, where drivers first focused on pressing the pedal fast enough to activate ABS instantly, before focusing on holding the indicator in the target zone, which was consistent with observations from Mims et al. [12]. If a participant met the criteria and passed the task, then a "yes" appeared. After reviewing the result for the given attempt, the task started over for the next one. See Figure 4 for an example of the results screen.

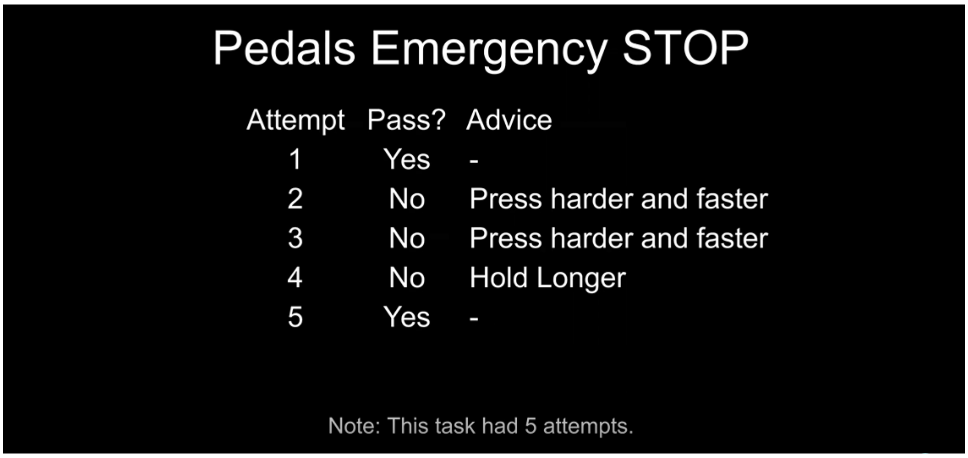

Figure 4. Example results page after all five targets of the *Pedals Emergency Stop© interactive* exercise.

3.1.4. Procedure

To group the participants by their previous ABS experience, they were asked if they had experienced ABS in a vehicle, followed by what the driver feels when ABS is activated during recruitment. During the study session, the participants read the consent form and provided their approval. This study was conducted in accordance with the Declaration of Helsinki and the protocol was approved by the Ethics Committee at Clemson University (IRB2019-447).

The participants then moved to the simulator and adjusted themselves to a comfortable distance from the pedals. They completed a short familiarization, where they pressed each pedal to achieve maximum travel five times, alternating between the gas and brake pedal to feel the full range of each pedal. The participants completed *Pedals Chase©* Level 2 with no more than three errors [20] within three attempts to move forward in the study.

Next, half of the participants heard and read the description of emergency braking prior to *Pedals Emergency Stop©*: "For this task, you will be practicing emergency braking. When emergency braking, the driver presses the brake pedal as fast and as hard as possible to get the vehicle to slow down quickly. It is common for the anti-lock braking system or ABS to activate during emergency braking. ABS activates to prevent the wheels from locking up. Locked wheels can cause skidding and loss of steering control. ABS quickly holds and releases brake pressure to prevent the wheels from locking up. As a result, the driver feels vibration and hears noise from ABS activating. To practice emergency braking you must release pressure from the gas pedal, lift your right foot up from the gas pedal and the floor, move it above the brake pedal, press the pedal as quickly as possible all the way down and keep full pressure on the brake pedal. You will experience vibration and noise to simulate ABS in the simulator, continue to hold down the brake pedal when you feel the vibration".

All the participants heard the following instructions for *Pedals Emergency Stop*© prior to the interactive exercise: "For this task you start off using the gas pedal. You will keep the indicator in the moving target zone. When the brake pedal target appears at the top of the pedal and you hear "Stop", press the brake pedal all the way down as quickly as possible. Hold the indicator in the target zone for 3 tones. Do you have any questions?". All the participants completed the first attempt of *Pedals Emergency Stop*©. The other half of the participants heard and read the description of emergency braking after the first attempt of *Pedals Emergency Stop*©. Then, all the participants received the explanation of the results page: "This screen shows how you did pressing the brake pedal for an emergency stop when ABS activates. The column on the left labeled "Attempt" shows each attempt or brake target you saw during the scenario. The middle column labeled "Pass" shows if your brake press was consistent with ABS activation. If you pressed the brake pedal fast and hard enough as well as held the indicator in the target zone for 3 tones you will pass. If you did not press the brake pedal fast and hard enough or did not hold the brake indicator in the target zone for enough time, you will not pass. The column on the right labeled "Braking Advice" shows how to improve your performance of pressing the brake to be more consistent with activating ABS. If you do not press the brake pedal fast and hard enough, you will receive the advice to press the brake faster and harder. If you do not hold the indicator in the target zone for 3 tones, you will receive the advice to hold longer". The participants completed the four remaining attempts of *Pedals Emergency Stop*©, then repeated *Pedals Emergency Stop*© two additional times for a total of 15 emergency braking attempts. Figure 5 provides an overview of the simulator protocol.

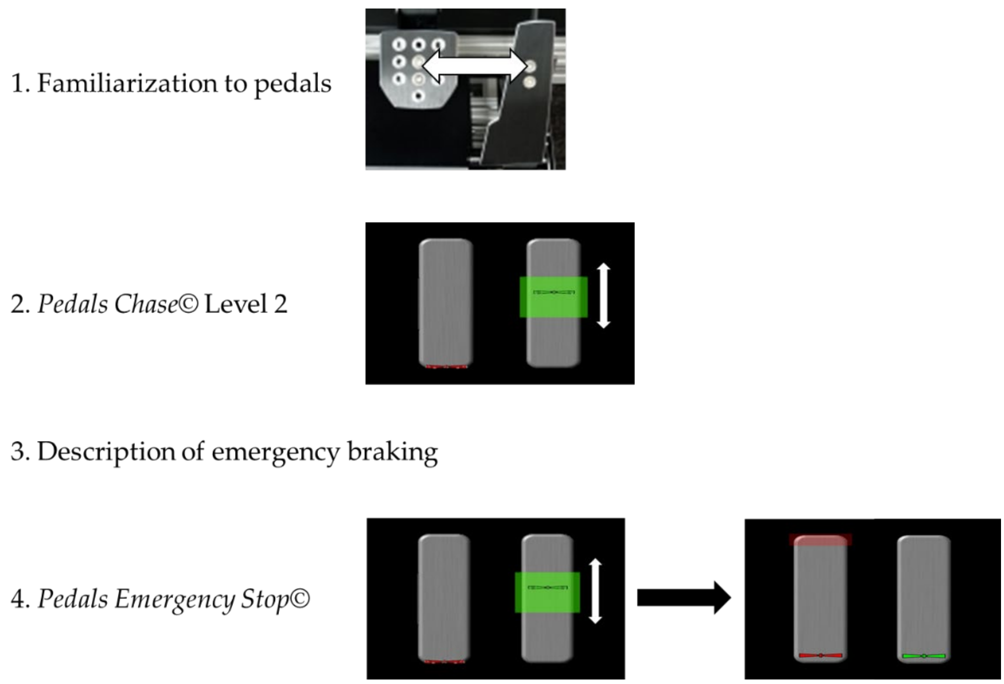

Figure 5. Overview of simulator protocol.

After completing *Pedals Emergency Stop*©, the participants completed a survey (see Table 2). The survey consisted of questions to investigate the required number of attempts, as well as usability statements inspired by the System Usability Scale. For the usability statements, participants responded to the statements using a five-point Likert scale ranging from strongly agree (rating of 1) to strongly disagree (rating of 5).

Table 2. Survey questions and response types.

Question	Response Type
Do you think you had enough emergency braking practice attempts?	Yes/No
- If yes, you completed 15 attempts, how many attempts did you need to feel confident receiving "passes"?	Open-ended
- If no, how many attempts would you like to have?	Open-ended
What was the hardest part of the emergency braking practice on the simulator?	Open-ended
I found the emergency braking practice on the simulator to be a practical tool.	1–5 Likert scale
I think my understanding of ABS was improved from the emergency braking practice on the simulator.	1–5 Likert scale
I feel as though it would be beneficial to practice using ABS in a vehicle in a parking lot or track after the emergency braking practice on the simulator.	1–5 Likert scale
I would recommend the emergency braking practice on the simulator for new drivers.	1–5 Likert scale
I would recommend the emergency braking practice on the simulator for refresher training.	1–5 Likert scale
I would recommend the emergency braking practice on the simulator for evaluating fitness to drive.	1–5 Likert scale
Do you have any suggestions or additional comments about the study?	Open-ended

3.1.5. Data Organization and Analysis

The data from *Pedals Emergency Stop*© and the surveys were combined and organized by participant. Participants that used their left foot to brake were not included in the analysis because they were considered outliers and were replaced.

To investigate differences between the groups, an analysis of variance (ANOVA) was utilized. The dependent variable was the number of attempts for the participant to receive a "pass", and the independent variable was the ABS experience (two levels) and when the description of emergency braking with ABS occured (two levels) for a total of four groups.

3.2. Results

3.2.1. Performance across All Trials

The percentage of participants that received a "pass" on each of the trials was tallied. The percentage of participants that passed dramatically increased over the first five trials from 18% to 80%. From trials six to 15, the percentage of participants that passed became more consistent, varying between 69% and 84% (see Figure 6).

A Chi-square test was conducted to investigate differences in the number of participants that passed and failed between all 15 trials. The results of the Chi-square test indicated a significant difference between the number of participants that passed and failed between the trials (χ^2 = 110.80, df = 14, p < 0.05). To determine where the differences were, follow-up Chi-square tests were conducted using a Bonferroni adjustment method, where the four comparisons were evaluated at a significance level of 0.0125. The results of the follow-up Chi-square tests indicated that the number of participants that "passed" during trial 1 was significantly lower than all the other trials (see Table 3). The Chi-square tests also found that the number of participants that "passed" during trial 2 was significantly lower compared to trials 5, 6, 10, 11, 13, 14 and 15 (see Table 3).

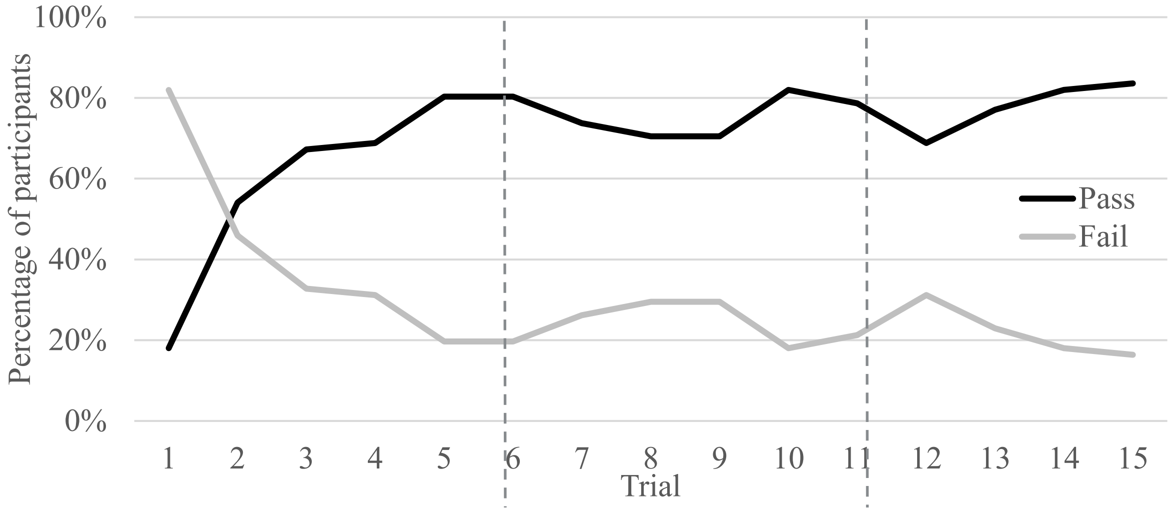

Figure 6. Percentage of participants to pass and fail on each trial. Note: Dotted vertical lines designate the breaks when restarting *Pedals Emergency Stop©*.

Table 3. Significant differences in the number of participants to pass and fail between trials.

Trials Compared (*df* = 1, *p* < 0.0125)		χ^2
Trial 1 (Pass = 11, Fail = 50)	Trial 2 (Pass = 33, Fail = 28)	17.205
	Trial 3 (Pass = 41, Fail = 20	30.165
	Trial 4 (Pass = 42, Fail = 19)	32.06
	Trial 5 (Pass = 49, Fail = 12)	47.357
	Trial 6 (Pass = 49, Fail = 12)	47.357
	Trial 7 (Pass = 45, Fail = 16)	38.158
	Trial 8 (Pass = 43, Fail = 18)	34.022
	Trial 9 (Pass = 43, Fail = 18)	34.022
	Trial 10 (Pass = 50, Fail = 11)	49.869
	Trial 11 (Pass = 48, Fail = 13)	44.934
	Trial 12 (Pass = 42, Fail = 19)	32.06
	Trial 13 (Pass = 47, Fail = 14)	42.595
	Trial 14 (Pass = 50, Fail = 11)	49.869
	Trial 15 (Pass = 51, Fail = 10)	52.473
Trial 2 (Pass = 33, Fail = 28)	Trial 5 (Pass = 49, Fail = 12)	9.522
	Trial 6 (Pass = 49, Fail = 12)	9.522
	Trial 10 (Pass = 50, Fail = 11)	10.892
	Trial 11 (Pass = 48, Fail = 13)	8.2656
	Trial 13 (Pass = 47, Fail = 14)	7.1167
	Trial 14 (Pass = 50, Fail = 11)	10.892
	Trial 15 (Pass = 51, Fail = 10)	12.383

The average number of trials "passed" was 10.6 (*SD* = 3.7). The participant with the poorest performance "passed" two trials (trial 11 and trial 14), while the individual with the best performance "passed" all 15 trials. The participants were grouped based on whether they had or did not have previous knowledge and experience with ABS, as well as on the order in which they received the description of emergency braking (for a total of four groups). There were no significant differences in the number of trials passed between the four groups.

3.2.2. Number of Trials to Pass for the First Time

When examining the number of trials for a participant to "pass" the first time, on average, it took participants three trials (*SD* = 2.26, *Min* = 1, *Max* = 11) to receive their first pass. The majority (85%) of the participants were able to "pass" within the first four trials (see Figure 7).

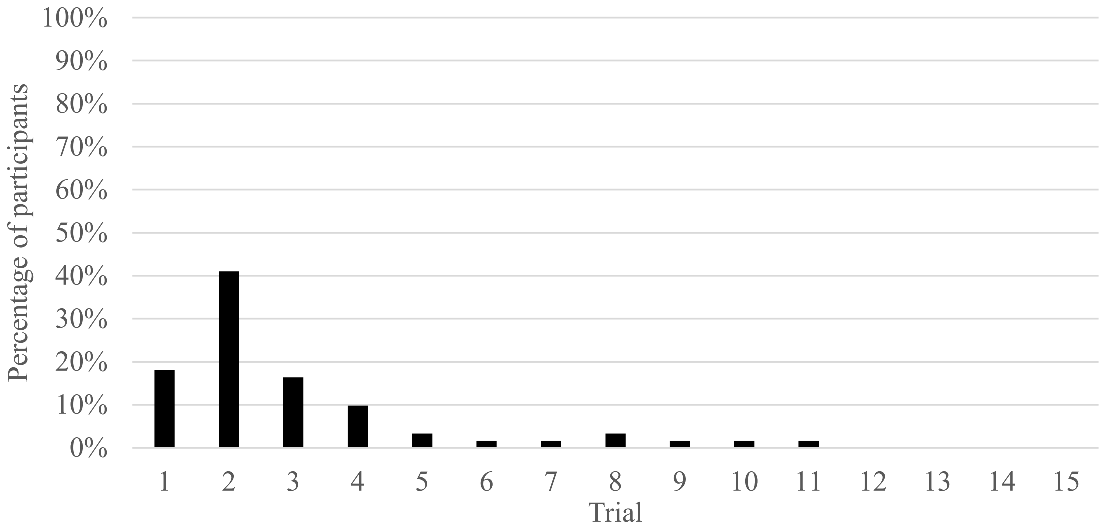

Figure 7. Participants first pass by trial.

Performance was evaluated based upon the participants' group, based on their previous knowledge and experience with feeling ABS activate, as well as by when they received the description of emergency braking during the *Pedals Emergency Stop*© interactive exercise. An analysis of variance (ANOVA) was conducted, where Levene's test for normality was not found to be significant, indicating no differences in variance between the groups, nor were there any significant differences found in the number of trials to pass for the first time between the groups.

3.2.3. Exercise Feedback (Advice)

When the participants did not "pass" a trial during the interactive exercise, the results screen for the *Pedals Emergency Stop*© interactive exercise displayed advice to help the individual improve their performance. The participants either received the advice to "press harder and faster" if their initial brake press was not consistent with ABS activation or "hold longer" if they did not hold the brake indicator in the target zone for the three tones. Over the 15 attempts during the *Pedals Emergency Stop*© interactive exercise, the participants did not "pass" 272 trials out of the 915 total trials. Almost all the advice displayed to participants was "press harder and faster" (99.3%). The advice "hold longer" was only displayed twice (both on trial 9, for two different participants).

3.2.4. Survey Results

After completing the interactive exercises on the simulator, the participants completed a survey to share their views of the emergency braking task.

Number of Trials

The participants were asked if they thought that they had enough emergency braking attempts on the simulator. The majority (91.8%) of participants thought that they had enough attempts and only 6.5% of the participants did not think that they had enough. One participant responded "maybe" to whether they had enough trials. For the participants that thought they had enough attempts, they were asked how many attempts were needed to feel confident receiving "passes". The average number of trials to feel confident was 5.6 trials. Interestingly, participants "passed" an average of 2.7 trials prior to the reported number of trials to feel confident. For the four participants who did not think they had enough attempts, they were asked how many more attempts they wanted to have, and the responses included two, five, 20 and 30 more attempts.

Hardest Part of the *Pedals Emergency Stop*© Interactive Exercise

The participants were asked what they thought the hardest part of the *Pedals Emergency Stop*© interactive exercise was during the survey. The most common response was pressing the brake pedal fast/hard enough (21%). Other common responses were getting used to the pedal feel/spacing (15%); getting used to the simulator setup/lack of steering wheel (13%); focusing on when the task switched to show the brake target (13%); the reaction time between pressing the gas and brake pedal (8%); and modulating the gas pedal to keep the indicator in the target zone (7%). The remaining responses were unique and did not overlap with other participants responses, accounting for less than 2% of the responses. These responses included "getting a pass"; "sitting still?"; "the pulse of the ABS coming through the pedal"; "spontaneity"; "the ABS simulation in the brake being more aggressive than I expected"; "the brake pedal needs to be pushed with the heel of the foot"; "timing"; "reactions"; "paying attention"; and "previously using non-ABS".

Usability Statements

The participants were asked to respond to statements using a 1–5 scale, where 1 was strongly disagree and 5 was strongly agree. The results suggest that the participants did not find the *Pedals Emergency Stop*© interactive exercise to be unnecessarily complex ($M = 1.28$); the interactive exercise was a practical tool ($M = 4.28$); the participants thought that their understanding of ABS was improved ($M = 4.05$); and that it would be beneficial to practice using ABS in a vehicle ($M = 4.22$). The majority of the participants recommended the ABS simulator task for new drivers ($M = 4.72$) and refresher training ($M = 4.16$). The only item with a score less than 4.0 was recommending the ABS simulator task for evaluating fitness to drive ($M = 3.88$). See Table 4 for a summary of the results.

Table 4. Results for the usability statements.

Statement	Goal	Average	Min.	Max.	SD
I found the emergency braking practice on the simulator unnecessarily complex.	1	1.28	1	3	0.52
I found the emergency braking practice on the simulator to be a practical tool.	5	4.28	2	5	0.76
I think my understanding of ABS was improved from the emergency braking practice on the simulator.	5	4.05	1	5	1.10
I feel as though it would be beneficial to practice using ABS in a vehicle in a parking lot or track after the emergency braking practice on the simulator.	5	4.22	1	5	1.02
I would recommend the emergency braking practice on the simulator for new drivers.	5	4.72	2	5	0.61
I would recommend the emergency braking practice on the simulator for refresher training.	5	4.16	2	5	0.90
I would recommend the emergency braking practice on the simulator for evaluating fitness to drive.	5	3.88	2	5	1.04

3.3. Discussion

The results of the study suggest that receiving a "pass" during the *Pedals Emergency Stop©* interactive exercise was achievable by all of the drivers. Not only did 85% of the participants receive their first "pass" within the first four trials of the interactive exercise, but there were no statistical differences between the participants with prior knowledge of and experience feeling ABS versus those without prior knowledge or experience. Neither were there differences between the participants who received the description of emergency braking prior to or after the first trial of the *Pedals Emergency Stop©* interactive exercise. Most participants felt that the simulator task was a practical tool.

Proposed *Pedals Emergency Stop©* Refinements

One of the opportunities for improvement that emerged during the study was to determine when the participants' performance began to "plateau". There was a learning curve, where it took participants four to five trials before 70–80% of all the participants were "passing". There was a steep increase in the percentage of participants that received a "pass" over the first three trials, which suggests that all participants, regardless of experience with ABS and the order of the emergency braking description, needed a few trials.

In terms of the feedback presented to the participants, it became obvious during the study that the results could be presented more effectively. DriveSafety, Inc. (Draper, UT, USA) has two interactive exercises that measure reaction time, both of which display feedback immediately after each trial and keep the results presented for the duration of the entire task. *Reaction Timer Steering©* measures the time that it takes a driver to turn the wheel either to the right or left in response to a stimulus. *Reaction Timer Stoplight©* measures the time it takes a driver to move their foot from the gas pedal to the brake pedal in response to a stimulus. During both interactive exercises, driver's reaction times are displayed after each trial, continuously populating as the driver completes all 16 trials. The trials are grouped into sets of four, consisting of a practice with four trials and three tests with four trials in each test. The DriveSafety clinical simulators utilize three separate screens, where reaction times are displayed in groups of four on the two outer screens. See Figure 8 for an example of the results for *Reaction Timer Stoplight©* where the task is displayed in the center.

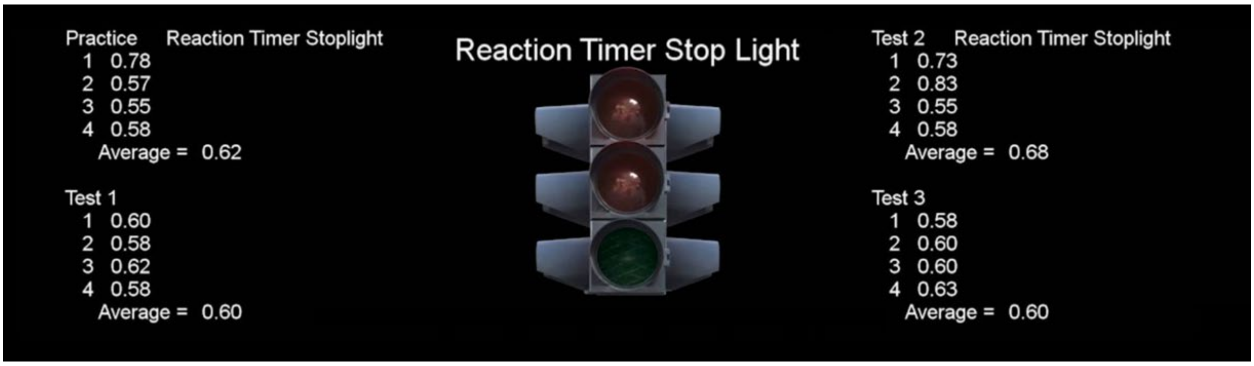

Figure 8. Results screen for *Reaction Timer Stoplight©*.

Second, since the participants who completed *Pedals Emergency Stop©* needed about four trials to begin to "pass" the interactive exercise, it may be beneficial to adopt the approach used in *Reaction Timer Stoplight©* and *Reaction Timer Steering©*, where there is a practice with four trials, followed by three tests with four trials each. Currently, *Pedals Emergency Stop©* rotates between the task screen with the pedals to the results screen, where the interactive exercise displays up to five attempts (see Figure 9).

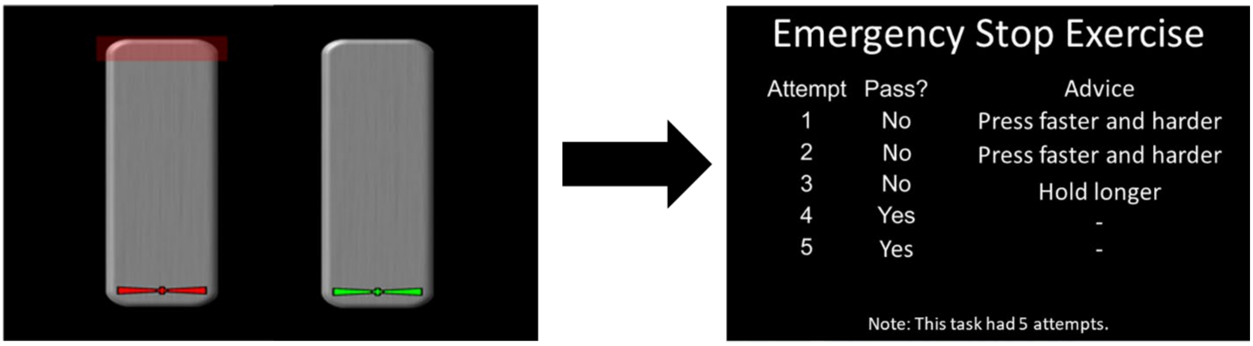

Figure 9. Current *Pedals Emergency Stop*© interactive exercise, which rotates between the task screen with the pedals and the results screen.

The next iteration of *Pedals Emergency Stop*© could utilize the full real estate of the screen(s) to continuously display the results in the same manner as the *Reaction Timer Stoplight*© interactive exercise, instead of rotating back and forth between the task and results screens. A potential proposed change is presented in Figure 10, where the task is in the center of the screen and the results populate on the outer edges of the screen.

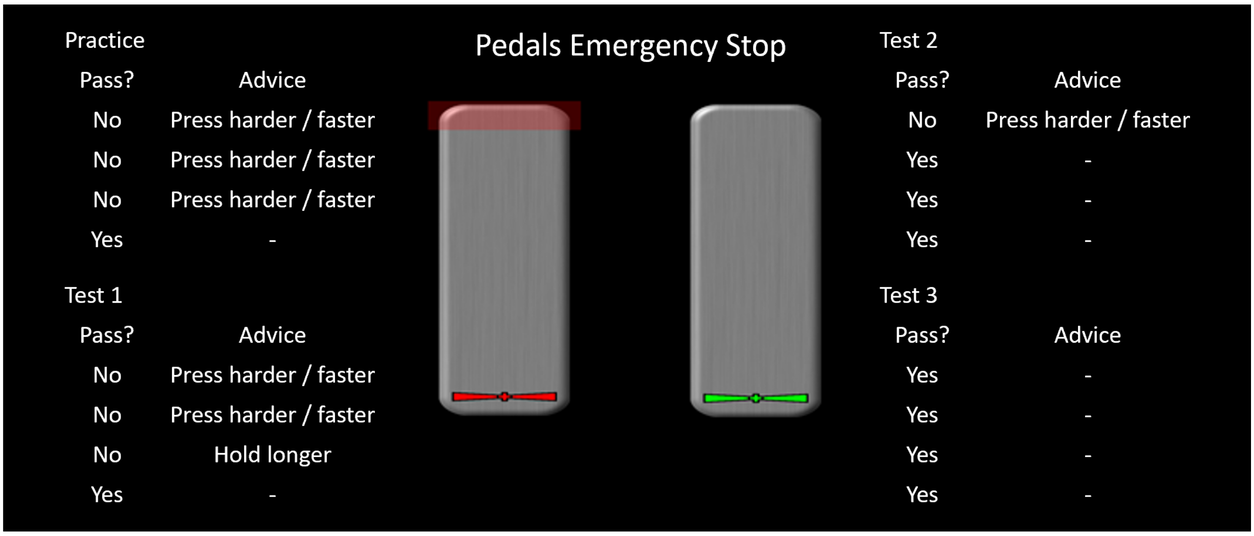

Figure 10. Example of the proposed *Pedals Emergency Stop*© combined task and results layout.

The third opportunity for refinement that emerged during this study was to develop criteria to determine if a participant "passed" the emergency braking task on the simulator. The results from the survey showed that the majority (92%) of participants felt they had enough attempts and felt confident after six trials. Participants "passed" an average of three trials prior to reporting feeling confident. Based on these results from the survey, the reasonable criterion to "pass" is three out of the four trials.

When applying this new model of four trials for the practice and three tests to the results in the current study, 73.8% of the participants would "pass" test 1, 78.7% after test 2, and 82% after test 3 (see Figure 11). Note that since the participants in the current study completed 15 trials instead of the proposed 16 trails, test 3 in the current study is one trial short and only contains three trials.

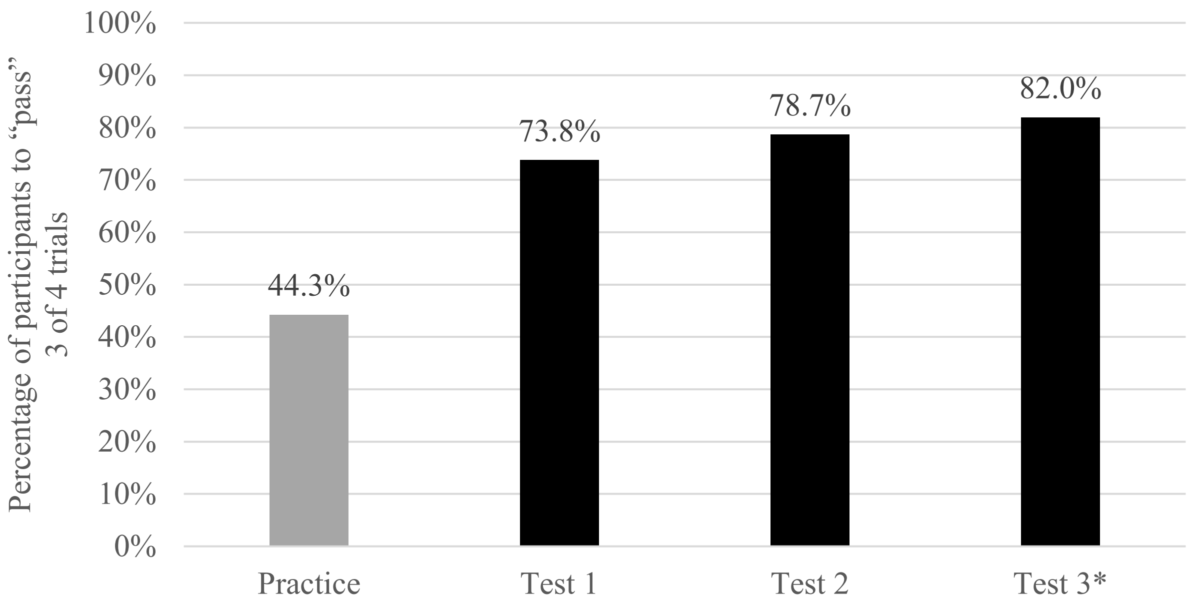

Figure 11. Percentage of participants to pass with the trials regrouped into sets of four with a practice, test 1, test 2 and test 3. * Test 3 only consisted of three trials because participants in the current study completed 15 trials.

4. Study II

A second study was conducted to investigate the proposed refinements to the *Pedals Emergency Stop*© interactive exercise that were identified during Study 1.

4.1. Materials and Methods

4.1.1. Participants

Individuals were recruited from a local manufacturing facility. A total of 39 participants completed this study. One participant was dropped because they did not pass the simulator task. The remaining 38 participants consisted of 31 males and seven females, with an average age of 34.2 years (*SD* = 13.9, *Min* = 18, *Max* = 60).

4.1.2. Procedure

The simulator protocol for Study 2 was similar to Study I, beginning with short familiarization, followed by the *Pedals Chase*© Level 2 interactive exercise. Next, all the participants received the description of emergency braking before completing the refined version of *Pedals Emergency Stop*© interactive exercise, consisting of a practice with four trials, followed by three tests with four trials each. If the participants "passed" three out of four trials in a test, they passed the simulator task. All the participants completed the practice and all three tests (16 total trials), regardless of whether a participant "passed" the test or not, in order to ensure that all participants received the same number of trials.

4.2. Results

For the 38 participants that completed the simulator task, they were all able to pass the warmup exercise, *Pedals Chase*©, with three errors or less within three attempts.

All the participants were able to "pass" three out of four trials of a test and, thus, passed the emergency braking task on the simulator; 94.7% of the participants passed during Test 1, 2.6% passed during Test 2, and 2.6% passed during Test 3. All the participants that passed Test 1 also passed Tests 2 and 3. The participant that passed Test 2 also passed Test 3. Once a participant passed a test, they continued to pass on the subsequent tests. On average, the participants "passed" for the first time in 1.8 trials (*SD* = 1.3), where 94.7% were able to "pass" during the practice (within the first four trials). For the 61 trials that the participants did not "pass", 95% of the feedback was to "Press harder and faster", and only 5% of the feedback was to "Hold longer".

4.3. Discussion

The *Pedals Emergency Stop*© interactive exercise prompted individuals to experience emergency braking with haptic ABS activation. The interactive exercise displays images of a gas and brake pedal with colored target zones. The interactive exercise begins with a gas pedal target that oscillates up and down, and then a stationary brake pedal target appears at the very top of the brake pedal at the same time that a "Stop" prompt is played. The participants are instructed to press the brake pedal as quickly as possible to move the brake indicator into the target zone and hold the indicator in the target zone for three tones. When the participant is in the target zone, haptic brake pedal feedback is provided. After each braking target, the participants are presented with a pass or fail result. To pass, the participants must press the brake pedal fast and hard enough, as well as hold the brake indicator in the target zone for three tones. If the participant does not pass the trial, they are presented with advice to improve their performance, either to "press harder and faster" or to "hold longer". The *Pedals Emergency Stop*© interactive exercise consisted of a practice with four trials, followed by three separate tests with four trials in each test. The participants had to "pass" three out of four trials on a test to pass the simulator practice.

The results showed that all but one of the 39 participants was able to pass the emergency braking task. Since 94.7% of the participants were able to pass the emergency braking task during Test 1, these results suggest that the criteria of "passing" three out of four trials within a test was achievable for almost all the participants. Moreover, once a participant passed a test, they continued to pass the subsequent tests, suggesting that once a participant begins to pass, they continue to pass. This may suggest that the criteria of passing three out of four trials is robust and representative of when a participant understands and is successful with the exercise. Interestingly, the participants in this study "passed" for the first time in an average of 1.8 trials, which is a fewer number of trials than observed in the previous study (Sections 2–4), where participants "passed" for the first time in an average of three trials. The difference in the average number of trials to "pass" for the first time could be due to changes to the layout of the *Pedals Emergency Stop*© interactive exercise, where the results for each trial were visible during the entire exercise in this study. In the previous study (Sections 2–4), the exercise only displayed the results after the completion of a trial, switching back and forth between the images of a gas and brake pedal, and the results for the trial. Similar to the previous study (Sections 2–4), the majority of the advice given to participants that did not "pass" a trial was to "Press harder and faster". The results of this suggest that the updates to the *Pedals Emergency Stop*© interactive exercise helped to improve participants' performance during the exercise, and that the criterion to pass the emergency braking task was reasonable.

5. Conclusions

The overarching goal of Study I was to evaluate a novel emergency braking task using a simulator and an interactive exercise, *Pedals Emergency Stop*©. The simulator was designed to provide haptic ABS brake pedal feedback. The *Pedals Emergency Stop*© interactive exercise prompted participants to press the brake pedal in a motion consistent with emergency braking when ABS activates, and provided repetition with that motion and the haptic feedback associated with ABS. The participants' goal was to press the brake pedal fast and hard to the maximum brake pedal travel and to hold that position for approximately three seconds in order to "pass" the trial. The participants had 15 trials during the task. The results showed that 85% of participants were able to "pass" for the first time within the first four trials, with an average of three trials to "pass". All the participants in this study received a "pass" a minimum of two times during the task. There were no differences in performance observed between participants with previous knowledge and experience feeling ABS versus those who did not have prior knowledge and experience with ABS. The results of the survey found that participants thought they had enough attempts, that the task was a practical tool, and recommended the task for new drivers and refresher training, as well as evaluating fitness to drive.

The proposed refinements to the *Pedals Emergency Stop©* interactive exercise were explored in a second study, where participants had four practice trials, followed by three tests with four trials in each test. To pass the emergency braking task on the simulator, the participants had to "pass" three out of four trials within a test. The results of the exploratory study revealed that the criterion to pass three out of four trials was reasonable.

The results of these studies suggest that the emergency braking task using the *Pedals Emergency Stop©* interactive exercise can be an effective tool for drivers to gain experience with emergency braking and haptic ABS feedback.

6. Limitations

The simulator utilizes a high end set of pedals for video game use. The feel and pedal type of the gaming pedals may not generalize to all passenger vehicles, since not all passenger vehicle pedals use a consistent design. The haptic ABS brake pedal feedback replicated one vehicle. Haptic feedback in passenger vehicles is not consistent across vehicles. In addition, in a vehicle, ABS activates at the wheel, outside of the passenger compartment. The sound of ABS in the simulator is generated from the device used to deliver haptic ABS feedback in the simulator, which is not the same device or system in a vehicle, nor does the sound come from the same place. The simulator did not include a steering wheel, simply because the task did not require the use of a steering wheel, but some of the participants did report that not having a steering wheel required a period of adjustment.

7. Future Research

The results of the survey show that the emergency braking task is recommended for new drivers, refresher training and evaluating fitness to drive. The current study involved the general driving population, consisting of individuals ranging from 18 to 60 years of age. Future efforts should consider the inclusion of new, teen drivers as well as older driving populations and at-risk driving populations. Future research should investigate the integration of the emergency braking task with driver's education for novice teen drivers. An anecdotal observation made during this study was that two participants used unique strategies to press the brake. While most participants lifted their foot right foot to operate both the gas and brake pedal, one participant pivoted on their heel when transitioning between the gas pedal to the brake pedal, which is not a typical strategy used during emergency braking (Xi, 2015). One other participant adjusted the chair backwards halfway through the simulator session and began braking with their heel instead of the ball of the foot. Performance during the emergency braking task could be influenced by foot movement strategy and/or by where the driver contacts the brake pedal; thus, future research should investigate if strategy and contact point influence the driver's ability to "pass". Future research should investigate how the emergency braking task on the simulator generalizes to on-road driving.

Author Contributions: Conceptualization, L.M., J.B., R.G., C.J. and K.M.; methodology, L.M. and J.B.; software, R.G. and K.M.; formal analysis, L.M.; investigation, L.M., C.J. and K.M.; resources, J.B., D.I. and K.M.; writing—original draft preparation, L.M.; writing—review and editing, L.M., J.B., R.G., C.J., D.I. and K.M.; visualization, L.M., R.G. and K.M.; supervision, J.B.; project administration, J.B. and K.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki and approved by the Institutional Review Board (or Ethics Committee) of Clemson University (protocol code IRB2019-447 and date of approval 4 March 2020).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Not applicable.

Acknowledgments: We would like to thank Tarun Muthuvelappan and Minar Kale for their assistance during the pilot testing of the simulator and interactive exercise. We would also like to thank Elenah Rosopa for her valuable comments on iterations of this manuscript.

Conflicts of Interest: Donnie Isley is employed at the BMW Performance Center and Ken Melnrick is employed by DriveSafety, Inc.

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