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Investigating Drivers' Knowledge and Experience With the Anti-lock Braking System (ABS) Which Led to the Development and Evaluation of an Emergency Braking Training Exercise Using a Driving Simulator With Haptic Pedal Feedback

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INVESTIGATING DRIVERS' KNOWLEDGE AND EXPERIENCE WITH THE ANTI-LOCK BRAKING SYSTEM (ABS) WHICH LED TO THE DEVELOPMENT AND EVALUATION OF AN EMERGENCY BRAKING TRAINING EXERCISE USING A DRIVING SIMULATOR WITH HAPTIC PEDAL FEEDBACK

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ABSTRACT

The purpose of this dissertation was to explore the extent to which drivers do or do not have knowledge of and experience with the anti-lock braking system (ABS) and then to explore the development and evaluation of a driving simulator task specifically designed to address emergency braking with haptic brake pedal feedback. The anti-lock braking system (ABS) was created to help drivers in emergency braking situations by preventing skidding and loss of control due to locked wheels. Vehicles with conventional (pre-ABS) brakes required the driver to "pump" the brake pedal, or to rapidly press and release the brake pedal, during an emergency braking situation. This act of rapidly pressing and releasing the brake pedal was difficult for many drivers. If the driver did not pump the brake pedal quickly enough, the result could cause the vehicle's wheels to lock and the driver to lose control of steering and braking of the vehicle. ABS automated the pumping action for the driver by holding and releasing the brake pressure to prevent the wheels from locking and skidding. Since ABS quickly holds and releases the brake pressure, the driver experiences a vibration or "thumping" in the pedal when ABS is engaged (Kahane, 1994). This vibration or "thumping" can be confusing for the driver. The National Highway Traffic Safety Administration (NHTSA) discovered that drivers did not understand the purpose of ABS, did not know when ABS was functioning, or if their vehicle was even equipped with ABS (Mazzae, Garrott & Snyder, 2001).

In the US, teenage drivers have an increased risk of being involved in crashes. To address the increased risk of teen crashes, post-license advanced driving programs have emerged. The first study within this dissertation gained teenagers' perspective of a half day post-license driving program focused on a hands-on introduction to emergency braking, skid recovery and the dangers of distracted driving on a closed-road track, the Guard Your Life (GYL) Challenge

program. The teenagers (N=134) completed a survey immediately following the program and a subset (N=50) of those teen completed a phone interview three months later. The open-ended survey and phone interview items reflected the program's key concepts of emergency braking, skid recovery and the dangers of distracted driving. During the follow-up phone interview, the majority of teenagers reported using the skills experienced and half of the participants who participated in the phone interview reported using skills that they learned to avoid a crash, where ABS braking was the most common skill used. Almost all teenagers reported anticipating or changing their driving behaviors, specifically by reducing distractions, having a heightened awareness and changing their driving position. The survey and follow-up phone interview results suggested that the teenagers benefited from the skills introduced and, from the teenagers' perspective, has helped them avoid crashes. The results of the study also suggested that teen drivers do not understand or have experience activating ABS prior to the program.

During study I, it was observed that the parents of the teenage drivers were engaged during the classroom portion of the study and the majority of the parents stayed to watch their teen drive on the track. Study II gained parents' perspectives while observing their teens' involvement in the GYL post-license driving program which focused on a hands-on introduction to emergency braking, skid recovery and the dangers of distracted driving. Parents (N=134) completed a survey after the program, and for comparison purposes, the teens (N=164) also completed a survey at the end of the same program. While the parents only observed the program, the results revealed that most learned useful information and would consider additional training for themselves. Interestingly, though 85% of the parents reported experiencing ABS, only 53% of the parents reported teaching their teen about ABS, with 87% of those parents discussing ABS and only 13% of parents providing hands-on practice to their teen. Almost all teens and parents reported anticipating changing their driving behaviors, specifically by reducing distractions, having a heightened awareness while driving and changing their driving/seating position. These results suggested that parents benefited from simply observing the class and though many parents reported experiencing ABS, the lack of hands-on practice the parents reported providing to their teen may suggest that some of these parents may not understand ABS.

In addition to evaluating drivers' views of the GYL program, study III aimed to gain the views of both teen and adult drivers' views of full day car control classes designed to address defensive driving skills through both classroom instruction and hands-on practice on a closed-road track. To obtain the views from teenagers (N=80) and adults (N=177), both groups completed a survey immediately after their classes, and a subset of the adults (N=64) completed a phone interview six months later. Results from the teenage and adult surveys showed that both groups reported the most important topics learned during the car control class were skid recovery, using ABS and looking where the car should go. Both teenagers and adults reported that they plan to significantly change their driving behaviors, especially those concerning seating, hand and mirror positions. Overall, after the class, the teenagers and adults felt "moderately competent" in their ability to perform the exercises practiced during the class, which increased from the rating of "not competent" prior to the class. The results from the phone interview with the adults suggest that ABS braking was the most important topic to them six months later. ABS braking was also the single-most reported skill used after the class and the self-identified skill most used to avoid a crash. The phone interview showed that the adults accurately predicted their use of the behaviors (seating position, vision, distractions, etc.) and turned those behaviors taught during the class into habits of their daily driving. The results from the teenage and adult surveys, as well as the phone interview with the adults, suggested that the participants benefitted from the knowledge and skills gained from the one-day car control class. Like the teens in study I, the adults reported using ABS braking the most on the road after the class of all of the skills addressed, thus adult drivers may not understand or have experience activating ABS prior to the class.

Study IV narrowed the focus to determine high school students' knowledge and experience with ABS. High school participants (N=60) with a driver's license were recruited from science classes to complete the survey. The results revealed that only 22% of the teens knew what ABS stood for and 23% could describe the purpose of ABS. Only 33% of the teens reported using ABS and 15% reported that they had practiced using ABS. Interestingly, there were no statistical differences in knowledge or experience with ABS between teens that had taken driver's education and those who had not. The results of the survey found the majority of teen drivers did not have knowledge of and experience with ABS. This study suggested that teen drivers, regardless of driver's education experience, did not have knowledge of or experience with ABS.

Understanding that not all drivers may have knowledge and experience with ABS, Study V investigated how a driver's knowledge and experience with ABS effected performance braking in a vehicle. Drivers (N=79) were recruited from adult car control classes which focused on defensive driving skills, including both classroom and behind-the-wheel instruction on a closed-road course. One focus of the class was activation of ABS, which was designed to help drivers during emergency braking situations. In the classroom, participants learned what ABS is as well as how and when it functions. On the closed-road course, participants learned how to activate ABS and how the system feels when it is activated. The goal of this study was to understand how knowledge of and experience with ABS prior to the class relates to a driver's ability to activate ABS. The participants' ability to activate ABS was evaluated by the driving instructors using a behaviorally anchored rating scale with five ratings, ranging from 1 representing no ABS activation to 5 corresponding to full ABS activation throughout the entire stop. Participants completed a survey before and after the class to gain an understanding of their knowledge of and experience with ABS. The results found significant differences in braking performance between participants with and without prior knowledge of the feel of ABS when activated, practice activating ABS, and training, both with and without an ABS braking component. Most of the drivers who had practice or training activating ABS were able to fully activate ABS on their first try, outperforming all other participants. These results suggested that drivers could benefit from practice focusing on emergency braking with ABS.

Study VI was a smaller study within study V, where participants (N=17) recruited from the adult car control classes. This study aimed to investigate if electrodermal activity (EDA) varied while drivers were completing the ABS exercise on the track. Participants wore Empatica E4 devices on both wrists to measure EDA. The EDA data were analyzed through skin conductance level (SCL), but the results showed no significant differences in SCL values between the right and left wrists, nor was there any consistency for which wrist had higher SCL values. The results from this study suggested that for an ABS braking task, SCL may not be the ideal measure of EDA.

Not all drivers have access to training or an experienced driver to help them practice activating ABS, thus a novel driving simulator with haptic brake pedal feedback and interactive exercise *Pedals Emergency Stop*© for drivers to practice emergency braking with ABS feedback was developed. The interactive exercise displayed images of a gas and brake pedal with colored target zones. The interactive exercise began with a gas pedal target that oscillates up and down, then a stationary brake pedal target appears at the very top of the brake pedal at the same time a "Stop" prompt was played. Participants were 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. In addition, when the participant was in the target zone haptic brake pedal feedback was provided. After each braking target, the participants were presented with feedback regarding if they passed or failed that trial. To pass, participants were required to 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 did not pass the trial, they were presented with advice to improve their performance, either to "press harder and faster" or to "hold longer".

During the initial evaluation of the emergency braking practice, participants (N=63) had 15 trials and were grouped base upon their knowledge and experience feeling ABS activate. The results found 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 participants in this study received a "pass" a minimum of two times during the practice. 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. Also, participants thought they had enough practice, that the practice was a practical tool, and recommended the training for new drivers, refresher training, as well as evaluating fitness to drive. The results of this study suggested that the emergency braking practice using the *Pedals Emergency Stop©* interactive exercise may be an effective tool for drivers to practice emergency braking with haptic ABS feedback.

As a result of the initial evaluation of the emergency braking practice, criteria to pass the emergency braking practice was proposed. The *Pedals Emergency Stop©* interactive exercise was divided into a practice with four trials and three tests with four trials each. The criteria to pass the emergency braking practice was passing three out of four trials within one of the tests.

The final study within this dissertation aimed to understand if the emergency braking practice on the simulator generalized to driving in a vehicle on a closed road course as well as to evaluate the proposed criteria to pass the simulator practice. Participants (N=69) were grouped according to their previous experience feeling ABS activate as well as if they completed the simulator practice. Participants in the simulator group completed the emergency braking practice with the *Pedals Emergency Stop*© interactive exercise for a total of 16 trials making up the practice and three tests. All participants attempted to activate ABS on the track, where their performance braking was rated by a professional driving instructor using the behaviorally anchored rating scale developed in the study V which consisted of five ratings, ranging from 1 representing no ABS activation to 5 corresponding to full ABS activation throughout the entire stop. Participants completed five attempts on the track, all at 35mph. This speed was chosen because it is the speed where most crashes occur. Since 97% of the participants that completed the simulator practice passed the practice, the results revealed that the criteria to pass three out of four trials was representative of a participant that was successful passing the *Pedals Emergency Stop*©. There were no significant differences in braking performance ratings on the track between participants that had completed the simulator practice and those who had not. This was also true for participants with and without prior experience feeling ABS activate, where no differences were found in performance braking rating on the track. Though braking performance on the track was not influenced by the simulator practice, 74% of the participants that completed the simulator practice thought they benefitted and/or their performance on the track was improved as a result of the emergency braking practice on the simulator with *Pedals Emergency Stop©*.

Though the speed of 35mph was selected because it is the speed where most crashes occur, future studies should include multiple speeds, both lower (35-45mph) and higher speeds (50-60mph). Study V observed that speeds between 35 and 50mph corresponded to drivers learning how hard and how quickly to press the brake pedal. As the speeds increased over 50mph, the stopping distance increased, and drivers learned to maintain brake pedal position and pressure until the vehicle came to a complete stop. Future research should explore the *Pedals Emergency Stop©* interactive exercise with novice teen drivers, who make up a disproportionate number of fatal crashes for their small percentage of the driving population (NHTSA, 2018b). Since the majority of teenage drivers' crashes can be attributed to driver error, which includes recognition errors (visual scanning errors, distraction), decision errors (following distance, vehicle speed relative to conditions), and performance errors (losing control; Curry, Hafetz, Kallan, Winston, & Durbin, 2011), the emergency braking practice on the simulator could help to address decision and performance related braking errors. Driver's education is commonly included in the graduated driving license process (NHTSA, 2017a) and integrating the emergency braking practice on the simulator with driver's education may help novice teen drivers understand emergency braking as well as the haptic brake pedal feedback associated with ABS activation through the repetition of trials as part of the *Pedals Emergency Stop©* interactive exercise.

As the automotive industry shifts focus to autonomous vehicles, the driving task will be eliminated and all individuals within the vehicle will become passengers. It is known from Study

VII that the haptic feedback from ABS in not only in the brake pedal, but can be felt through the entire vehicle. Future autonomous vehicle users may experience the feedback from ABS as passengers. If the user does not understand the feedback nor given information about what the feedback is doing, this could lead to the user losing trust in the autonomous vehicle. Future autonomous vehicles should consider the impact that ABS feedback could have on user trust and methods to provide information to users to help communicate that the feedback back is part of normal emergency braking operation.

DEDICATION

I dedicate this to my wonderful parents, Nancy and Steve, sister Stephanie, extended family and friends for their support, faith, and patience throughout this process.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

NOTATION

ABS	Anti-lock braking system
ADAS	Advanced driver assistance system
ANPRM	Advanced notice of proposed rulemaking
ANOVA	Analysis of variance
BARS	Behaviorally Anchored Rating Scale
CCC	Car control class
CDC	Center for Disease Control
CDS	Clinical driving simulator
CPR	Correct pause recover
DMV	Department of Motor Vehicles
DOT	Department of Transportation
ECU	Electronic Control Unit
EDA	Electrodermal activity
ESC	Electronic stability control
EU	European Union
FARS	Fatality Analysis Reporting System

FMVSS	Federal Motor Vehicle Safety Standards
GDL	Graduated Driver's License
GVWR	Gross vehicle weight rating
GYL	Guard Your Life
HLDI	Highway Loss Data Institute
HR	Heart rate
IIHS	Insurance Institute for Highway Safety
IRB	Institutional Review Board
LTVs	Light trucks and vans
M	Mean
NADS	National Advanced Driving Simulator
NHTSA	National Highway Traffic Safety Administration
NTDETAS	Novice Teen Driver Education and Training Standards
OEM	Original equipment manufacturer
SAE	Society of Automotive Engineers
SCL	Skin conductance level
SCR	Skin conductance response

SD	Standard deviation
SgRP	Seating reference point
SNS	Sympathetic Nervous System
SUS	System Usability Scale
SUV	Sport Utility Vehicle
TR	Total responses
US	United States
VIN	Vehicle Identification number
WHO	World Health Organization

CHAPTER ONE: INTRODUCTION

1.1 Motivation

The motivation for this dissertation stems from the opportunity to volunteer with the Guard Your Life Challenge Program, which is a half day advanced post-license program. The program focuses on introducing teen drivers to emergency braking with ABS, skid recovery and distracted driving through exercises on a closed-road track. During my time volunteering, it became obvious that the teens do not understand basic physics principles nor standard safety equipment on vehicles. These observations lead to further investigation into drivers' understanding and experience with ABS.

1.2 Overview of the Dissertation Document

Chapter two is a literature review of existing research surrounding ABS. This chapter begins with an overview and development of ABS. Section 2.2 describes the crash rate evaluations conducted on vehicles with ABS and the National Highway Traffic Safety Administration's (NHTSA) Light Vehicle ABS Research Program Tasks. The third section gives an overview of how ABS and ESC overlap functionally, and the resulting crash rate evaluation associated with the combination of both systems.

Chapter three is the first survey study, conducted to gain teenage drivers' views on an advanced post-license program that introduced participants to ABS braking, skid recovery and distracted driving. Section 3.1 provides background information on teenage crash statistics, US license requirements, driver's education, and safety focused vehicle technology. The section continues to describe post-license driving programs and provide detail on the Guard Your Life Challenge Program that the teenage drivers participate in. Section 3.2 describes the methods used to administer the survey and phone interview as well the corresponding questions. Section 3.3 presents the results of the study, where teenage drivers reported learning and using the skills from the class on the road. The discussion, section 3.4, relates the Guard Your Life Challenge to other post-license driving programs. Lastly, section 3.5 provides the overall conclusions from the survey study. The results of the survey demonstrated the teens the learned the primary objectives taught in both the classroom and behind-the-wheel instruction. The results of the follow-up phone interview conducted three months after the class showed that the most used skill teenagers reported using was ABS braking and it was also the skill most used to help the teens avoid crashes. The results suggest that teen drivers do not understand or have experience activating ABS prior to the program (Mims et al., 2020b).

Like chapter three, chapter four is a survey study. The goal of this study was to gain the parents' views of the Guard Your Life Challenge Program in addition to a new group of teens. The first section introduces the parent's role in their teenager's experience learning to drive followed by a description of the Guard Your Life Program. Section 4.2 presents the methods used to administer the survey as well as the details of the survey. The results are investigated in section 4.3, which show that though parents were observing their teen participate in the Guard Your Life Program, the parents learned new information thought to be beneficial. Section 3.4 combines the discussion and conclusions of the study. The results of this study showed that the knowledge the teens learn in the class (i.e., positioning in the vehicle, where to look while driving, function of vehicle safety systems, etc.) may not be known by the parents and the adult population may benefit from similar programs. The findings also showed that though many parents reported experiencing ABS, the small percentage of parents that provided hands-on practice to their teens may suggest that parents may not understand ABS (Mims et al., 2020a).

Chapter five is a third survey study, aimed to gain the views of both teens and adults participating in a one-day car control class that focuses on defensive driving skills on a closed-road track. The introduction covers information on driver's education and licensing, crash statistics of both teen and adult drivers, post-license driving programs, and an overview of the car control class. Section 5.2 describes the data collection methods and contents of the surveys. Section 5.3 presents the results, showing that both teen and adult drivers learned from the class and adult drivers used the skills from the class on the road. The discussion in section 5.4 compares the results from the teens and adults as well as overlaps with the previous two studies. The last section, 5.5 provides the conclusions from the study. Though this study included more exercises than the previous teen study (Mims et al., 2020a), the most used skill on the road to avoid a crash was ABS. This result suggests that most adults and teens do not have understanding or experience using ABS prior to the class and practice activating ABS may be an essential skill (Mims et al., 2020c).

Chapter six, the fourth survey study, has a narrow focus to determine if high school students have knowledge of and/or experience using ABS. Section 6.1 provides an overview of investigations into driver's experience with ABS as well as driver's education guidelines for knowledge and experience with ABS. The methods section (Section 6.2) describes the survey and how the data were collected. The results of this study (Section 6.3) show that the majority of teen drivers do not have knowledge and experience with ABS as well as there no statistical difference between teens that took driver's education and those who had not. Section 6.4 contains the discussion and conclusions, which show the similarities between the results and other investigations into driver's knowledge and experience with ABS. This study suggests that regardless of driver's education experience, teen drivers do not have knowledge or experience using ABS.

Chapter seven aimed to evaluate adult drivers' ability to activate ABS on a track. The introduction (Section 7.1) gives an overview of ABS and the ABS exercise that is part of the car control class, where participants were recruited from. Section 7.2 describes the pre- and post-test used to gather prior knowledge and experience with ABS as well as their experience during the class. This section describes the behaviorally anchored rating scale developed to quantify how instructors to evaluate driver's performance activating ABS, where a rating of 1 equated to no activation and a 5-rating corresponded with full activation of ABS through the entire stop. Section 7.3 contains the results, which suggest that drivers with prior knowledge and experience activating ABS were more likely to fully activate ABS during their first attempt of multiple and needed fewer attempts to fully activate ABS. The discussion (Section 7.4) compares the practice or training method between the car control class and other researchers' methodologies. The study suggests that ABS practice or training may be required to fully activate ABS (Mims et al., 2021).

Chapter eight investigated variations in electrodermal activity (EDA) while drivers were activating ABS on a track. The introduction (Section 8.1) provides an overview of ABS, EDA and braking, multiple arousal theory as well as the car control classes that participants were recruited from. Section 8.2 introduces the Empatica E4 wearable device that was used to measure EDA on both wrists and how the EDA data was analyzed through the skin conductance level (SCL). The results (Section 8.3) suggest no significant differences between the SCL values between the right and left wrists, though there was no consistency for which wrist showed higher SCL values. Section 8.4, the discussion, relates the findings to other braking related studies with EDA. The results from this study suggest that SCL may not be the correct measure of EDA to investigate and skin conductance responses (SCRs) should be explored. The ability to measure SCR is limited by the technology that exists today that is appropriate for track use with paying participants, and research on EDA was discontinued from this dissertation.

Chapter nine introduces the development and evaluation of a driving simulator for emergency braking practice with haptic ABS feedback. The introduction (Section 9.1) provides an overview of previously explored ABS training and the use of simulators for driver's training. Section 9.2 describes the development of the simulator and *Pedals Emergency Stop*© interactive exercise for emergency braking practice and the initial usability study to ensure that the *Pedals Emergency Stop*© interactive exercise worked as designed. The usability study showed the majority of participants were able to exhibit the correct braking behavior within the first five attempts (Section 9.2.2), but also identified improvements based on feedback from the usability study participants and the changes made as a result (9.2.3). Section 9.3 describes the evaluation of the *Pedals Emergency Stop*© interactive exercise. The results from this study (Section 9.3.3) verified the changes from the usability study as well as discovered there were no differences in performance during the *Pedals Emergency Stop*© interactive exercise based on a participant's previous experience with ABS nor when the participant receives the description of emergency braking with ABS. The discussion (9.3.4) identifies the proposed updates to the *Pedals Emergency Stop*© interactive exercise and pass/fail criteria for the emergency braking practice, where participants are given four practice trials followed by three tests each consisting of four trials, where participants' goal is to "pass" three out of the four trials in a test.

Chapter ten aims to evaluate the differences in driver's ability to fully activate ABS on a track between participants that completed an emergency braking practice using the *Pedals Emergency Stop*© interactive exercise and those who did not. Section 10.1 provides an overview of other researchers' investigations into ABS training. Section 10.2 describes the proposed methods for the emergency braking practice using the *Pedals Emergency Stop©* interactive exercise, on-track data collected, and data analysis. The results of the study are contained in 10.3, which outline the results from the simulator and on-track braking exercise that did not show differences in the driver's ability to activate ABS between participants that completed the simulator practice and those who did not. The discussion (10.4) verifies the criteria developed to pass the emergency braking practice on 'the simulator and identifies differences between the on-track braking exercise results with previous research. The results of this study suggest that the criteria developed to determine if a driver passed the emergency braking practice on the simulator is representative of a proficient driver but suggests no improvement in braking performance for drivers that participated in the simulator practice, limitations of the study and suggestions for future research.

Chapter 11 provides conclusions from the completed studies within the dissertation document (Section 11.1). An overview of future applications for the findings of this dissertation are discussed in 11.2.

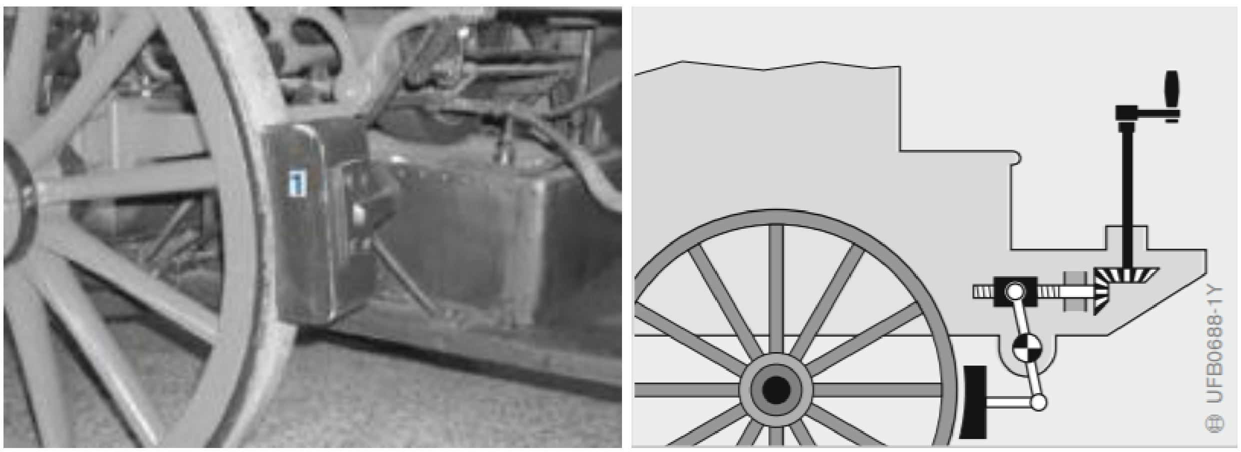
CHAPTER TWO: OVERVIEW OF THE ANTI-LOCK BRAKING SYSTEM (ABS)

2.1 Overview and Development of ABS

The anti-lock braking system (ABS) was created to help drivers retain control of the vehicle in a panic or emergency braking situation. ABS prevents the brakes from locking up, which can cause skidding or loss of control. When a vehicle's wheel is locked, it cannot rotate and is skidding across the road surface. Drivers are not able to steer when the vehicle's wheels are locked, regardless of the amount of steering input. Before ABS, vehicles had conventional brakes (non-ABS), which lock up when excess braking pressure is applied, like during panic braking. Conventional brakes require the driver to "pump" the brake pedal or press and release the brake pedal rapidly. Pumping the brake pedal at the necessary frequency was difficult for drivers and if performed incorrectly could result in locked wheels causing loss of control of the vehicle's steering and braking. ABS essentially does the brake pedal "pumping" for the driver by automatically holding and releasing brake pressure rapidly to prevent the wheels from locking up. When ABS rapidly holds and releases the brake pressure, it creates a vibration or "thumping" feedback in the brake pedal that the driver feels. ABS functions by monitoring the speed of each individual wheel and as the speed of a wheel approaches zero, indicating the onset of lock up, ABS activates to prevent the wheel from locking. For ABS systems that involve all four wheels, ABS prevents all wheels from locking, thus the driver retains steering control throughout the braking event (Duffy, 2009; Kahane, 1994).

2.1.1 Overview of Automotive Brakes

Brakes emerged on the first vehicles as the mechanism to bring vehicles to a stop. A vehicle's brakes were required to slow the vehicle's speed, bring the vehicle to a complete stop, slow the vehicle during downhill acceleration, and keep the vehicle from moving when stopped (Reif, 2014). Brakes slowed the rotation of the wheel; thus, the design of brakes was dependent on the wheel type. Early vehicles (late 1800s) with wooden or steel outer wheel surfaces had shoe, spoon, or wood block brakes, which used a wooden block to press against the outside of the wheel through mechanical connection (see Figure 1a [Reif, 2014]). The driver operated these early brakes using a hand levers. See Figure 1(b) for an example of a hand lever that was operated by rotating the handle to move the brake to the wheel (Reif, 2014).

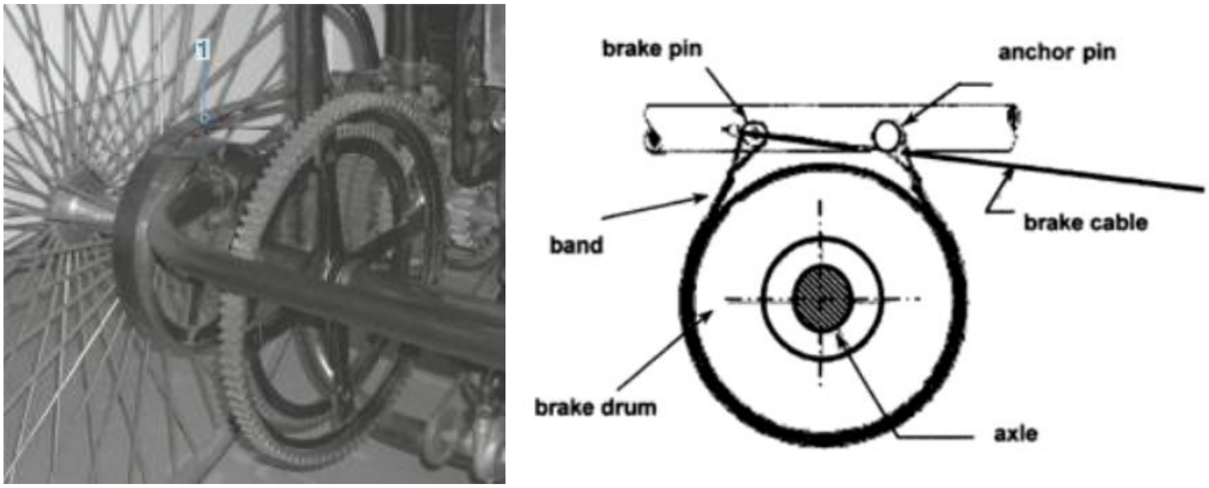


(a) (b)

Figure 1. (a) Wooden wheel with shoe brake (b) schematic of the connection between the hand lever and the shoe brake, where the turning of the hand lever moves the shoe brake towards the wheel (Reif, 2014)

With the emergence of rubber tires on early vehicles (late 1800s), shoe type brakes contacting the outside of the wheel were no longer able to be used. The friction created by shoe brakes on the outside surface of the wheel degraded the rubber tires much faster than wood or steel wheels, needing a new brake design. In 1898, band brakes began appearing on vehicles with rubber tires. Band brakes consisted of a drum mounted on the rear axle that tightened around the axel to slow the vehicle. The drum was tightened by a band that wraps around the outside of the drum and is attached to a lever that the driver operated by depressing a foot pedal (see Figure 2

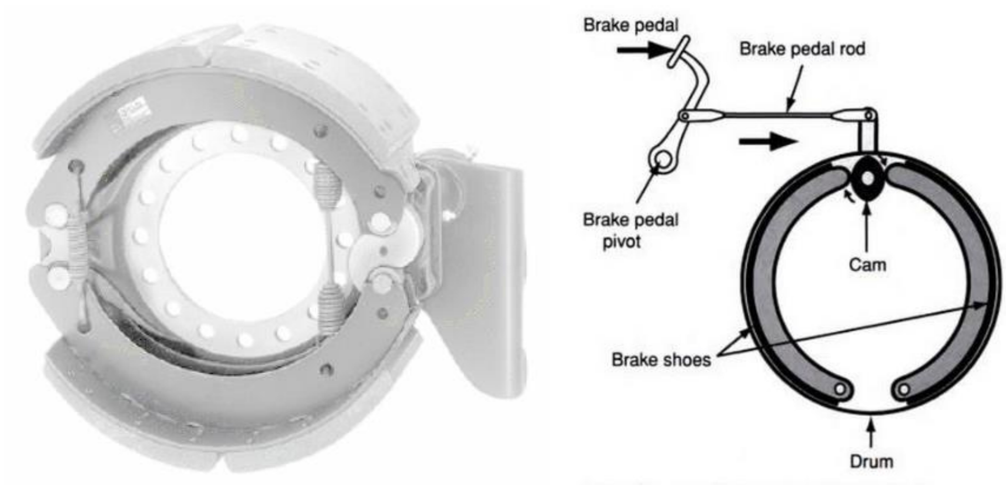
[Reif, 2014]). Though this design was better than the shoe brake design, there were issues with overheating, unpredictability, and unwrapping of the brakes on hills (Metcalfe & Metcalfe, 2006). Interestingly, in some instances when there were brakes on both the front wheels and rear wheels, the driver used a pedal brake to control the front brakes and a hand brake to control the rear brakes, which was consistent with Daimler vehicles from 1899 (Reif, 2014).



(a) (b)

Figure 2. Band brake on vehicle with rubber tires (a [Reif, 2014], b [Metcalfe & Metcalfe, 2006])

In 1902, Louis Renault patented drum brakes (Evolution of Hub Brakes, 1915). Drum brakes are mechanically actuated, where brake shoes within the wheel push outward to press against the drum, slowing the vehicle down (see Figure 3). Drum brakes were an improvement over band brakes because they reduced issues with overheating, increased responsiveness, and offered the ability to use lighter metal materials (Metcalfe & Metcalfe, 2006). The majority of the vehicles in the early 1900s were rear-wheel drive, or the engine powered the rear wheels only and the brakes were only on the rear wheels (Mavrigian & Carley, 1998). Prior to World War I, vehicle speeds and traffic density were low, thus the demand for braking performance was low. After the war, vehicle speeds began to increase as well as the demand for increased braking power (Newcomb, 1989). Early solutions added additional band brakes, which could require the driver to operate multiple brake pedals as well as a hand brake depending on the brake system configuration (Reif, 2014). With more powerful brakes, the likelihood that the brakes could prevent the wheel from turning, causing the wheel to lock dramatically increased. When the wheel will lock is dependent upon tire adhesion and the distribution of the braking force (Newcomb, 1989). With the distribution of braking force only on two wheels, locked wheels were more likely and locked rear wheels caused skidding or loss of control of the vehicle. In order to distribute the braking force more evenly, the need for brakes on all four wheels became apparent. Vehicle manufacturers were challenged to implement front brakes that did not interfere with the steering or front suspension systems. Ideally, the front brakes would lock prior to the rear brakes because locked front wheels continue in the direction of the momentum of the vehicle, but steering control is lost (Newcomb, 1989). By the 1920s, drum brakes became more common on all four wheels to improve braking performance and help prevent wheel lockup (Metcalfe & Metcalfe, 2006). The four brakes were connected using cables that ran to a brake pressure rail that connected to a single brake pedal; this configuration was common through the 1950s (Reif, 2014).



(a) (b)

Figure 3. Drum brake assembly (a [Day, 2014], b [Erjavec, 2003])

Hydraulic brakes were invented by Malcom Loughead in 1918. Brakes had been mechanical systems, using a system of rods and cables to move the brake shoe. Since liquids cannot be compressed, applying pressure to the pedal would evenly transfer the force to each brake, which was not achievable with a mechanical system, making a hydraulic system more predictable and safer. The first vehicle with hydraulic brakes emerged in 1920 from Duesenberg, followed by Chrysler in 1924 (Mavrigian & Carley, 1998). Hydraulic brakes spread to other automotive manufacturers and by the 1940s, hydraulic drum brake systems were common (Metcalfe & Metcalfe, 2006).

Power brakes were the next major innovation, where a vacuum was created within the brake system to make the brake pedal easier to press. The first vacuum assisted brake system was offered by Cadillac in 1930. In the 1950s, Bendix patented a vacuum booster system, that is more common with vehicles from the 21st century. In the 1960s, power brakes were offered as an upgrade option and by the mid-1970s power brakes were standard on vehicles (Mavrigian & Carley, 1998).

Though drum brakes were a dependable solution for a long period, increases in vehicle weight and engine power (increased speed) revealed drum brakes' performance limits. Disc brakes utilize a different design, where brake pads squeeze a spinning rotor that is attached to the axel to slow the vehicle down (see Figure 4). Disc brakes have multiple advantages over drum brakes, primarily the ability to cool faster because of the smaller contact of the friction pad against the rotor as opposed to drum brakes where the inner shoe brakes pressed against nearly the entire surface area of the drum. Disc brakes did not trap water due to their external design were the brake assembly hovered over the brake rotor. Drum brakes' circular shape on the inner portion of the wheel could trap water and cause faster degradation. The design of disc brakes also reduced weight (Mavrigian & Carley, 1998). Though disc brakes were patented in 1902 (Metcalfe & Metcalfe, 2006), they were not common in the US until the late 1960s and early 1970s. Disc brakes appeared on European race cars in the 1950s before being adopted by other sporty or luxury passenger cars in the 1960s, before becoming common on economy vehicles (Mavrigian & Carley, 1998). Early disc brakes produced loud sounds from the metal-on-metal friction, but in 1907 asbestos brake linings were created to reduce the noise (Metcalfe & Metcalfe, 2006).

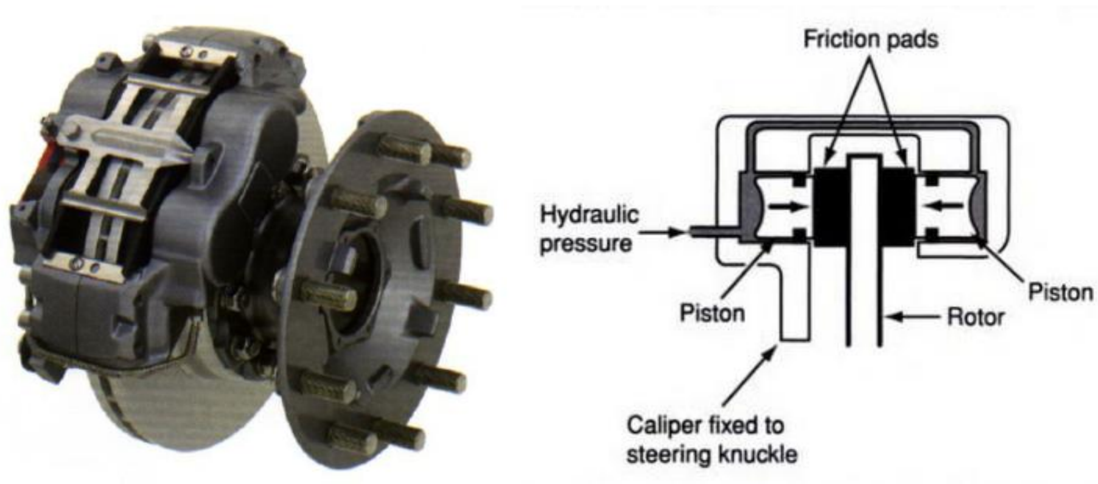


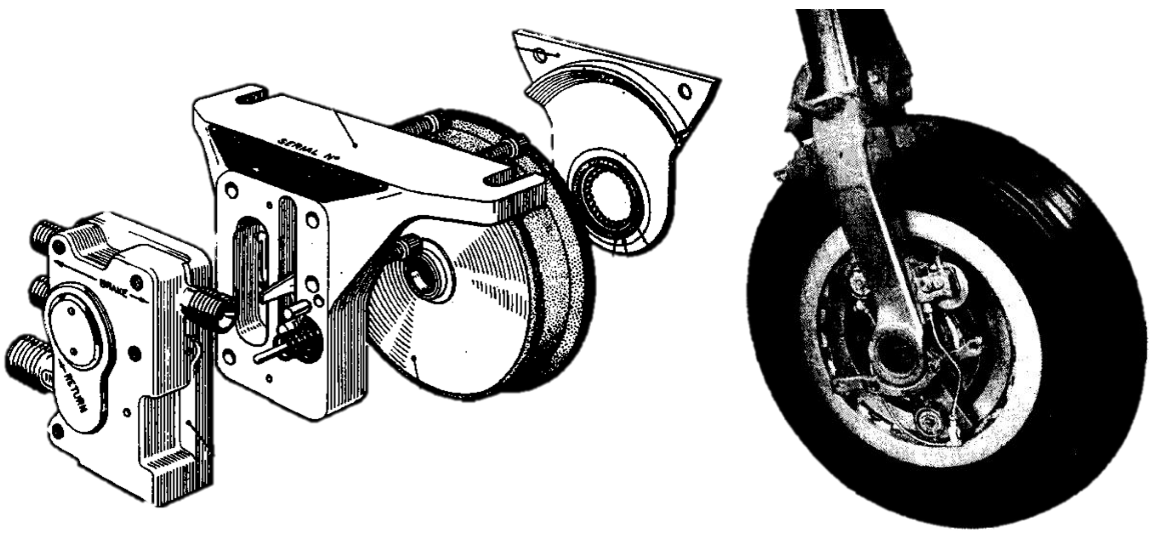
Figure 4. Disc brake assembly (a [Day, 2014], b [Erjavec, 2003])

In 1967, the initial Federal Motor Vehicle Safety Standards (FMVSS) list was released, including FMVSS 105 designating stopping distance, deceleration rates, and dual master cylinder requirements. Drum brakes were able to meet these initial standards, but when National Highway Traffic Safety Administration (NHTSA) updated FMVSS 105a effective in 1976 for passenger cars and in 1983 for light trucks and vans (LTVs, which also includes sport utility vehicles) it was much harder for drum brakes to meet the more stringent stopping requirements (Kahane, 2015). This pushed automotive manufacturers towards disc brakes, and many OEMs began using a mix of disc brakes on the front two wheels and drum brakes on the rear two wheels (Mavrigian & Carley, 1998).

2.1.1 Development of ABS

The development of ABS dates back to the early 1900s, beginning with railway vehicles (i.e., trains, locomotives, subways, etc.). In 1909 James Edward Francis published two patents addressing rail slip or skidding during acceleration and braking through control of the motor

(Francis, 1909a) and brake fluid-pressure (Francis, 1909b). Francis's contributions led to the concepts of modern-day ABS and traction control systems (skid prevention during acceleration). The aviation industry was the next transportation sector to gain interest in anti-skid devices. Airplanes were experiencing flat and exploding tires during landings due to their high speed. The pilots were not braking hard enough and as a result, taking long distances to stop (Madison & Riordan, 1969). Voisin Freres, the first commercial aircraft manufacturer formed in 1906 (Abbott & Bamforth, 2019) experimented with brake pressure modulation to reduce wheel slip during braking in 1920 (Lawes, 2014). Crane developed the first anti-skid device for airplanes named the Hydro Aire Hytrol Mark I anti-skid system, which was featured on a 1947 Boing B-47 (Mooney, 2013). In 1952, Dunlop introduced their anti-skid device for airplanes named the Maxaret (Johnson, 2010).



(a) (b)

Figure 5. (a) Aviation Maxaret assembly (b) Maxaret on airplane wheel (Flight International, 1953)

Interestingly, the first automotive focused anti-skid patent was granted to Karl Wessel in 1930 for the introduction of a brake pressure regulator concept for motor vehicles (Wessel, 1930). In 1932 Werner Moehl was granted a patent titled “An Improved Safety Device for Preventing Jamming of the Running Wheels of Automobiles when Braking” (Moehl, 1932), which was similar to Wessel’s 1930 patent. Bosch patented their own anti-skid device 1936 titled “Vorrichtung zum Verhüten des Festbremsens der Räder von Fahrzeugen" (Robert Bosch GMBH, 1936). Though these patents were published, the production of a working system was never achieved.

Great Britain began recording national road accident and casualty data in 1926 (Department for Transport, 2007) by the Road Research Laboratory or better known today as the Transport and Road Research Laboratory, which was established in 1993 by the UK government (TRL, 2021). Due to World War II, the Road Research Laboratory’s efforts were refocused through the 1940s on efforts related to the war (Department of Transportation, 2007). It wasn’t until the early 1950s that the British Road Research Laboratory identified skidding in automobiles as a concern. The British Road Research Laboratory found that skidding caused a significant number of crashes on wet roads, about 16,000 crashes or 27% of all crashes on wet roads in Great Britain in 1957. In 1958, the first International Skid Prevention Conference was held in Charlottesville, VA to begin to explore solutions, about 50 researchers attended (Johnson, 2010). One of the first solutions explored by the British Road Research Laboratory explored to see if the Maxaret anti-skid device for airplanes could offer similar benefits for automobiles. The Maxaret was retrofitted for a 1950 Morris 6 automobile, which required modifications for both the anti-skid device and vehicle. The results of retrofitting the Maxaret onto the Morris 6 prevented the brakes from locking, but the stopping distance was dramatically increased along with violent vibrations and sluggish steering (Johnson, 2010). The increase in stopping distance was attributed to a lack of braking efficiency as well as the lack of responsiveness to mild wheel slip. These problems stemmed from the Maxaret system being designed for a much larger airplane, that traveled faster and was heavier than a vehicle (Johnson, 2001). As a result, the British Road Research Laboratory worked with Dunlop to develop a Maxaret prototype for specifically for automobiles. The prototype was integrated into a Jaguar Mark VII, which was selected for having disc brakes as opposed to drum brakes (Johnson, 2010).

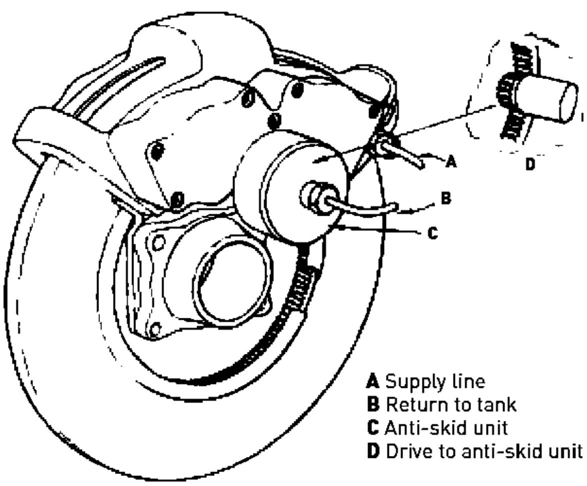


Figure 6. Dunlop's Maxaret ABS on disc brake (Johnson, 2010).

Creating an automotive specific Maxaret allowed for solutions to the sluggish steering, lack of responsiveness and stopping distance issues. Though these problems were solved, the Maxaret had issues with reliability and the feedback was still intense, so much so that the feedback could send the driver lurching forward while braking (Johnson, 2001). The Maxaret device was available to the automotive market in 1966 on the Rolls Royce Silver Shadow (Johnson, 2001), but the device was expensive, costing more than three times the cost of an economy car in 1966 (£2,000 versus £600). The automotive Maxaret device failed to capture the market but inspired other companies to invest in R&D of anti-skid devices throughout the 1960s (Johnson, 2010).

Many of the major automotive manufacturers partnered with brake system suppliers to develop their own ABS, which included: Kelsey-Hayes with Ford, Bendix with Chrysler, Alfred Teves with BMW, Bendix-DBA with Citroën, and Telxix GmbH with Diamler-Benz. GM was the only automotive manufacturer who did not partner with another company and conducted R&D internally (Johnson, 2010).

Ford used a similar approach to Dunlop by retrofitting an aircraft anti-lock unit into a 1954 Lincoln, which performed similarly to the British Road Research Laboratory's experiment with the Maxaret. Ford continued experimenting throughout the 1950s, before partnering with Kelsey-Hayes to develop the Sure-Track Brake system (Johnson, 2001; Madison & Riordan, 1969). Ford and Kelsey-Hayes decided to focus on developing a two-wheel system (rear-wheel only) due to cost concerns. There was research showing that drivers lacked the ability to recover control of a vehicle (counter steer) in a rear-wheel skid, that caused the vehicle to rotate (yaw), which resulted in a loss of control of the vehicle (Johnson, 2001). A two-wheel system (rear-wheel) would help prevent the rotation, thus eliminating the difficult recovery maneuver (Johnson, 2001). The drawback to a two-wheel system was the front two wheels could lock-up during hard braking and the driver would lose steering control (Kahane, 1993). Ford and Kelsey-Hayes decided the two-wheel system (rear-wheel) would be an addon to the existing brakes. The Sure-Track's control system measured the velocity of the rotation of the rear axle and tracked the vehicle velocity using the speedometer. The electronic control unit used the velocity measurements to calculate the deceleration and acceleration values. The deceleration and acceleration values between the rear axle and the speedometer were compared. When the deceleration rate of the rear axle was much higher than the vehicle's deceleration, indicating the onset of wheel lock-up, the Sure-Track Brake system activated at four cycles per second. Unfortunately, the pedal and noise feedback from the Sure-Track Brake system was more intense than the feedback from Maxaret, which cycled at 6 cycles per second, making it smoother. The addition of the Sure-Track Brake system did not reduce stopping distances more so than a driver pumping conventional brakes, but the Sure-Track Brake system showed promise in preventing the vehicle from rotating (yawing/spinning) out of control from locked rear-wheels. Due to the added cost of the Sure-Track Brake system, it was only included on luxury Ford and Lincoln vehicles, like the Maxaret (Johnson, 2001).

Chrysler began development of their Sure-Brake system in 1957, partnering with Bendix. Unlike Ford, Chrysler and Bendix were focused on creating a four-wheel brake system because of the increased control, preserving the driver's ability to steer during hard braking. The cost associated with a four-wheel braking system was greater than a two-wheel system, but the cost-to-benefit ratio pushed Chrysler and Bendix toward the four-wheel system. The goal for the Sure-Brake system was to stop in a shorter distance than a driver that could accurately pump the brake pedal to stop a vehicle with conventional brakes during hard braking. The Sure-Brake was electronically controlled and monitored velocity at each individual wheel. The velocity at each wheel was monitored using magnetic sensors on the front wheels and spring-loaded gears for sensors on the rear wheels. Deceleration and acceleration were calculated by an electronic system, which were used to monitor the state of each wheel. The Sure-Brake system did not compare deceleration rates between the wheels, instead their system compared the individual wheel deceleration rate to predetermined parameters that indicated the onset of wheel lock-up. The system cycled at 6 cycles per second, like the Maxaret system, which produced "jerky" feedback. Though the Sure-Brake system offered reduced stopping distances in a laboratory setting, the system had problems on the road, particularly because the electronic system was sensitive to salt. Due to the salt sensitivity, it was insulated to avoid the ability to come in contact with salt. Since the system used magnetic sensors on the front wheels, there were issues with electromagnetic interference from the radio and surrounding broadcast towers that caused the system to fail. Even though insulation was added to help with the interference, the insulation was not able to completely eliminate system failures (Johnson, 2001).

The initial introduction of ABS to market began in 1966 with the Maxaret device on the Jensen FF, 1969 Lincoln Mark III and Ford Thunderbird with the Sure-Track system (Johnson, 2010), and 1971 Chrysler Imperial with the Sure-Brake (Douglas & Schafer, 1971). The Maxaret, Sure-Track Brake and Sure-Brake were the first generation of ABS, which relied on vacuum power. In 1966, the first tailpipe emissions standards emerged in California. The Federal Air Quality Act of 1967 gave California the ability to create its own regulation for air quality and the Federal Clean Air Act of 1970 allowed California to set stricter emissions standards (State of California, 2021). Stricter emissions regulation caused the available vacuum power to decrease by about 40%, which was not enough to power ABS. In addition to power source issues, R&D resources were reallocated to respond to the oil crisis in 1973. ABS research did continue, but the production of ABS was halted through the mid-1970s (Johnson, 2001). The first generation of ABS from the 1960s had reliability issues caused by the electronic equipment. Though the production of ABS was halted, there were improvements in electronics and technology during that time. By the end of the 1970s signal processing was much faster, more reliable and less expensive (Johnson, 2001).

One of the most influential companies in ABS development is Teldix, who began their work on ABS in 1963. Teldix was a producer of electronics for aircrafts that became a subsidiary of Robert Bosch, GmbH (Johnson, 2001). The goals of the system that Teldix and Bosch would produce aimed to shorten stopping distance during a stop with locked wheels, steerability and stability. Unlike their competitors, Teldix's system was named Anti-Blockieren System, which utilized a high speed and high-pressure valve (Johnson, 2001). The system Teldix developed was able to pulse 10 times faster than Dunlop’s automotive Maxaret (Johnson, 2010). Not only did Teldix want to create a more responsive system, the requirement of shorter stopping distances on dry and wet pavement was also a major focus. The Maxaret device and anti-skid devices being developed by Dunlop, Kelsey-Hayes with Ford, and Bendix with Chrysler, were designed to react to wheel lock up after it began. Instead of creating a reactive device, Teldix designed a system that detected and regulated skidding, which allowed the driver to retain steering control. The Tedlix system used an electronic control module that monitored deceleration at each wheel to compare to the other three wheels as well as the direction of the vehicle. When a wheel was nearing a locked state, a spike in deceleration signaled high-speed valves to pulse, changing the brake pressure to prevent the wheel from locking (Johnson, 2010). The ability to detect wheel slip directly from the deceleration rate of each wheel allowed the system to adjust to changes in the coefficient of friction of the road surface. The other systems, Maxaret, SureTrack Brake and Sure-Brake, operated at a predetermined point, not accounting for the differences in the road surface. The electronic control system for the Anti-Blockieren system was both electronic and digital, requiring over 1,000 semiconductors in the prototype. The prototype system was not intended to be a commercial solution due to its expense and how fragile the prototype was. Bosch turned to Siemens and American Microsystems to create an LSI circuit that would replace the large number of semiconductors. As a result, Teldix and Bosch's system introduced the microprocessor to vehicles and automotive manufacturing (Johnson, 2010).

The first generation of ABS, Maxaret, Sure-Track Brake and Sure-Brake systems, was not known to be reliable due to electronic issues. Teldix and Bosch had to overcome the skepticism of the previous ABS systems and newly introduced electronic systems. Teldix and Bosch were able to overcome the skepticism surrounding ABS because their system relied on different technology that increased reliability. Teldix and Bosch's ABS was introduced in 1978 on the Mercedes S-class (Johnson, 2010). After the introduction of Teldix and Bosch's ABS reset the industry standards for how ABS should perform and became the model for ABS design (Johnson, 2001). By the late 1980s many of the automotive manufacturers began equipping vehicles with ABS and ABS quickly became available on multiple vehicle models within each automotive brand (Johnson, 2010). By 1994, ABS was available equipment on over 50% of new passenger cars (Kahane & Dang, 2009).

Though Teldix and Bosch pushed performance standards for ABS forward, there were vehicles equipped with two-wheel (rear-wheel) ABS on the market. Rear-wheel ABS was common on light trucks and vans (LTVs) vehicle classification, which includes not only light trucks and vans, but also SUV’s, minivans and full-size vans. LTVs typically are rear-wheel drive vehicles, meaning the power from the engine is sent to the rear wheels as opposed to the front wheels like many passenger cars. Rear-wheel ABS only functions on the rear wheels and is intended to prevent rear wheel yawing (rotating). Since rear-wheel drive vehicles are more likely to yaw and result in crashes caused by lack of directional control, rear-wheel ABS is intended to prevent catastrophic loss of traction that could cause rear-wheel yawing. Rear-wheel ABS does not engage on the front wheels, thus in the case of panic braking, the front wheels have the possibility to lock and steering control to be lost. Rear-wheel ABS began appearing on LTVs as early as 1987 but was commonly offered as standard equipment in 1990 on most US LTVs. Four-wheel ABS began appearing on some SUVs and vans in 1989. Though two-wheel systems were popular for LTVs initially, four-wheel systems eventually replaced the two-wheel systems (Kahane & Dang, 2009) and by 2004 there were no US manufactures that equipped LTVs with rear-wheel ABS (Kahane, 2015).

Current ABS are comprised of three major components: wheel-speed sensors, an electronic control unit (ECU), and hydraulic modulator. The wheel speed sensors measure deceleration and acceleration at each wheel and send the measurements to the ECU (Reif, 2014). Wheel speed sensors measure an AC voltage from a ring of teeth on the brake disc that rotates as the wheel moves (see Figure 7 [Erjavec, 2010]).

Figure 7. ABS ring (circled in yellow) on disc brake (Lawes, 2014)

The ECU interprets if a wheel is slipping or nearing lock-up based on the deceleration readings from the wheel speed sensors. If a wheel nears lock-up the ECU signals the hydraulic modulator to quickly hold and release the brake pressure at the wheel nearing lock-up. The hydraulic modulator consists of solenoid valves that control the hydraulic circuits that open and close to modulate brake pressure. Today’s vehicles utilize hydraulic systems with a dual master cylinder, which transfers brake pedal input from the driver to the individual brakes. The intake valve is responsible for building pressure within the hydraulic system and is located between the master cylinder and the wheel-brake cylinder. The exhaust valve is where the pressure is released, which is located between the wheel-brake cylinder and the return pump. When ABS is not activated, the intake valve is open and the exhaust valve is closed, so pressure can be built and sent to the wheel-brake cylinders when the driver presses the brake pedal. When the ECU signals the hydraulic modulator that lock-up may occur, the intake valve closes so pressure cannot increase. If the ECU senses that lock-up is still incurring, the exhaust valve opens to release pressure. When the exhaust valve is open brake fluid is drawn back from the brakes to reduce pressure in the wheel-brake cylinder through a pump, which reduces brake pressure, so the wheel does not lock (Reif, 2014). Brake pressure is then built back up by closing the exhaust valve and opening the intake valve. See Figure 8 for a schematic of the components of ABS.

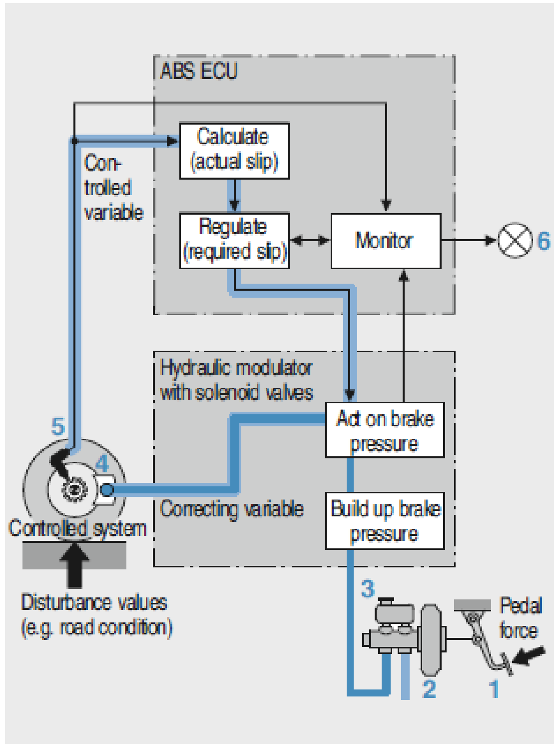


Figure 8. ABS components and control (Reif, 2014)

2.2 Evaluation of ABS

Between 1988 and 1991 NHTSA completed a series of two studies focused on ABS's effects on the vehicle's ability to stop on different road surfaces and during various vehicle maneuvers (Hiltner, Arehart &Radlinski, 1991; Arehart, Radlinski & Hiltner, 1992; Kahane, 1993). The Hiltner, Arehart and Radlinski (1991) study evaluated nine different ABS systems over various road surfaces as well as during different vehicle maneuvers, including straight line, curves and a lane change. Arehart, Radlinski and Hiltner (1992) published a follow-up study a year later, which included additional road surfaces but only during straight line braking. The studies included 12 different cars and 2 light trucks with four-wheel ABS as well as 3 trucks with rear-wheel ABS. The road surfaces vehicles included dry concrete, three different types of wet asphalt or concrete representing levels of smoothness, wet Jennite (slippery, road sealant), wet epoxy (slippery, similar to ice), and gravel. The vehicles were driven through each condition and maneuver with and without ABS enabled. For the vehicles with four-wheel ABS, there was no significant cases of yawing (loss of lateral stability, vehicle rotates) when ABS was enabled, but this was not the case when ABS was disabled, especially on wet surfaces. The trucks with rear-wheel ABS showed reductions in the yawing with ABS enabled, but it was not completely eliminated in comparison to the four-wheel system. The rear-wheel system was able to keep the amount of yaw less than 10 degrees in the wet conditions and less than 45 degrees on the wet Jennite. When the rear-wheel ABS was disabled, yawing was above 45 degrees in wet conditions, including the Jennite. The vehicles were also tested on non-homogenous surfaces, where one half of the surface was slicker than the other to resemble surfaces with slick patches. Overall, both rear-wheel and four-wheel ABS were able to minimize yaw as opposed to emergency stops where ABS was disabled, and yaw was commonly 180 degrees or more. For the tests involving braking and steering, such as stopping on a curve or a lane change, four-wheel ABS was effective at retaining steering capability and maneuvering successfully. Rear-wheel ABS was not effective when steering input was required because the front wheels locked during hard braking, thus losing steering control (Kahane, 1993). Changes in stopping distance between vehicles with and without ABS, were not consistent, especially for the trucks with rear-wheel ABS. Four-wheel ABS did not offer much benefit for dry conditions but reduced stopping distance by an average of 14% on wet concrete / asphalt, 10% on wet epoxy and 43% on wet Jennite. Four-wheel ABS did lengthen stopping distance on gravel by 28% when compared to when ABS was disabled. Interestingly, rear-wheel ABS lengthened stopping distance on all surfaces, with the exception of wet Jennite. Since the rear wheels were rolling and the front wheels were locked, there was not an expected benefit in stopping distance when comparing to vehicles with ABS disabled, where all four wheels were locked and sliding. These studies found that four-wheel ABS had significant benefits over rear-wheel ABS, including reductions in stopping distance, lateral stability, and steering control (Kahane, 1993). These studies were executed by expert drivers who could fully activate ABS and perform the evasive steering maneuvers while activating ABS, which would be challenging for a typical driver (Kahane & Dang, 2009).

In 1991 Congress introduced the Highway Safety Act, which gave NHTSA authority to conduct vehicle and highway safety related research. In section 2507 of the Highway Safety Act, it was suggested for NHTSA to adopt Federal Motor Vehicle Safety Standards (FMVSS) to require ABS for all passenger vehicles, including cars, multipurpose vehicles and trucks manufactured after September 1, 1996 (Congressional Research Service, 1991). To determine if ABS was a viable candidate for NHTSA to make standard safety equipment, evaluations of crash rates between vehicles equipped with ABS and without ABS were conducted.

Due to the influx of vehicles with rear-wheel ABS in the later 1980s, rear-wheel ABS was evaluated for effectiveness by crash data before four-wheel ABS. In 1993, NHTSA published the first evaluation of rear-wheel ABS, comparing crash involvement of light trucks and vans (LTVs, which also includes sport utility vehicles) with and without rear-wheel ABS (Kahane, 1993). The evaluation consisted of LTV crash data collected from the Fatal Accident Reporting System (FARS; 1989 to mid-1992), Pennsylvania (1989-1991), Michigan and Florida (1990-1991). The vehicles included in this evaluation were primarily US LTVs manufactured by Chevrolet, Ford and Dodge, consisting of vehicles from the first two model years with rear-wheel ABS compared to the last two model years before ABS.

Crashes are classified by the first harmful event, or “the first event during a crash that caused injury or property damage” (NHTSA, 2020 pp. ix). Crashes are first categories as either as single-vehicle or multiple-vehicle crashes. Multi-vehicle crashes can be further divided to the area where the collision occurred, which includes head-on, rear-end, angle and sideswipe. Multi-vehicles crashes occur with other vehicles in-transport on the roadway, including stalled disabled or abandoned vehicles. Single-vehicle crashes can be divided into three categories: collisions with fixed objects, collisions with objects not fixed and non-collisions. Fixed objects are “stationary structures or substantial vegetation attached to the terrain” (NHTSA, 2020 pp. ix), which include posts, ditches, trees, guard rails, bridges, etc. Collisions with objects that are not fixed includes crashes with parked vehicles, trains, pedestrians, cyclists or other nonoccupants. Non-collision crashes encompass other types of crashes, which mainly consists of rollovers (vehicle resting on its side or roof), but also includes vehicle fires, injuries within the vehicle and falling from the vehicle (NHTSA, 2020). Like multi-vehicle crashes, single-vehicle crashes can also be broken down by the area of first impact.

The results from the investigation showed significant reductions in run-off-road crashes, but not necessarily for multi-vehicle crashes. For nonfatal run-off-road crashes, the reduction in crash rates was observed for every type of LTV regardless of the road condition. There were approximately a 30-40% reduction in rollover crashes, 15-30% reduction in side impacts with fixed objects, and 5-20% reduction in frontal impacts with a fixed object. These reductions were expected due to the goals of rear-wheel ABS, to reduce irreversible loss of control during hard braking. The same trend was not observed for fatal run-off-road crashes, where only one vehicle, the Ford Ranger, showed a significant reduction (29%) in rollovers and side impacts with fixed objects (Kahane, 1993).

For collisions with pedestrians, animals, bicyclists, trains or other on-road objects, there were significant reductions in both fatal and nonfatal crashes. Fatal crashes were reduced by 5-15%, where the majority were reductions in vehicles contacting either pedestrians or bicyclists, causing fatal injuries. Nonfatal crashes were reduced by 10-20% but were mostly reductions in collisions with animals (Kahane, 1993).

Multi-vehicle crashes showed little to no effect on crash rates for nonfatal crashes. Fatal multi-vehicle crash results were inconclusive due to the small increases in involvement of LTVs role as the striking vehicles and the small reductions in crashes where the LTV was moving (as opposed to stopped). Given the nature of rear-wheel ABS, it was not expected that there were no significant effects on multi-vehicle crash rates. During heavy braking, a vehicle equipped with rear-wheel ABS's front wheels will lock-up and the driver will not be able to steer. Rear-wheel ABS's purpose is to prevent catastrophic loss of control that would result in a run-off-road crash, not eliminate all loss of control, hence why multi-vehicle crashes had no net effect (Kahane, 1993).

The Highway Loss Data Institute (HLDI) conducted an analysis on accident claims to study the effect of four-wheel ABS on collision and property-damage-liability claims with cars. The results of the study found little effect on insurance-reported accident rates of cars. The data did contain a large percentage of low-speed collisions, which were unlikely to be affected by ABS. The HLDI concluded that ABS could have a net zero effect, where any positive effects were offset by negative effects (as cited in Kahane, 1994).

Understanding the benefits of four-wheel ABS over rear-wheel ABS on a multitude of surfaces and maneuvers, as well as the initial positive evaluation of rear-wheel ABS, prompted the need for a formal investigation into four-wheel ABS. On January 4, 1994, an advanced notice of proposed rulemaking (ANPRM) requested information about the benefits and effectiveness of ABS (Federal Register Notice 59: 281), requiring NHTSA to investigate ABS's effect on crash rates and if ABS should be required safety equipment on new vehicles.

The initial evaluation of four-wheel ABS was published in December of 1994, which consisted of crash data from 1989 until 1993 solely on passenger cars. Nonfatal crash data were collected from Florida, Pennsylvania and Missouri between 1990 and 1992, as well as fatal data from FARS between 1989-1993. Since ABS had started being voluntarily installed on vehicles in the mid-1980s, the data used during the initial evaluation of ABS consisted of the first group of vehicles equipped with ABS on the road. The results showed significant decreases in multivehicle crashes on wet roads, with an estimated 24% reduction in fatal crashes and 14% reduction in nonfatal crashes. There were also decreases on snowy or icy roads, where a 13% reduction was observed for fatal and 11% for nonfatal crashes, but these reductions were not significant. These results were consistent with the findings from the stopping distance test, where ABS significantly decreased stopping distance on a wet or slippery surface when compared to vehicles without ABS. Little to no effect was observed on multivehicle crashes with dry road conditions compared to wet and snowy or icy road conditions. There was approximately a 27% decrease in fatal collisions with pedestrians and bicyclists (Kahane, 1994).

Though there were significant reductions in some crash scenarios mostly multi-vehicle crashes, there were significant increases in the number of run-off-road crashes. The estimated increase for fatal crashes was 28% and 19% for nonfatal crashes. Run-off-road crashes consist of rollovers, side, and front impacts with fixed objects. Typically, rollovers and side impacts with fixed object crashes are associated with a vehicle that has completely lost directional control (steering). The results found that rollovers and side impacts with fixed objects were associated with 40% increases in fatal and 28% increases in nonfatal crashes. Separately, rollover crashes showed a 23% increase (non-significant) in fatal and 49% increase in nonfatal crashes, while increases in side impact collisions with nonfixed objects, resulted in a 57% increase in fatal crashes and a 22% increase in nonfatal crashes. For collisions with frontal impacts with fixed objects, it is most likely that the driver has some steering control before the impact with the fixed object. The increase for frontal impacts with fixed objects for vehicles equipped with ABS were 19% (non-significant) for fatal and 15% for nonfatal crashes. The increases in run-off-road crashes were sustained for varying road conditions including dry (29% increase in fatal and 17% increase in nonfatal crashes), wet (17% non-significant increase in fatal and 24% increase in nonfatal crashes), and snowy or icy road conditions (36% non-significant increase in fatal and 19% non-significant increase in nonfatal crashes [Kahane, 1994]).

The results of this investigation suggested a dichotomous trend, where multi-vehicle crashes on wet roads significantly decreased (-24% for fatal crashes and -14% for non-fatal crashes) while single-vehicle run-off road crashes significantly increased (+28% for fatal crashes and +19% for nonfatal crashes, [Kahane, 1994]). With the decrease and increase, there was no evidence of crash rate reductions in ABS equipped passenger cars for both fatal and nonfatal crashes. It was unknown if the increase in crashes was due to the system itself, driver's use of the system, or a combination of the system and the driver (Kahane, 1994).

In 1995, NHTSA conducted additional analyses on the crash trends with vehicles equipped with ABS using state and FARS data. The studies focused on rollovers, side impacts with parked vehicles or fixed objects, frontal impacts with parked vehicles or fixed objects, and frontal impacts with another motor vehicle in transport, which are the types of crashes that ABS was anticipated to reduce. One of the studies focused on light trucks equipped with both rear-wheel and all-wheel ABS (Hertz, Hilton & Johnson, 1995a), and the other study solely focused on passenger cars with all-wheel ABS (Hertz, Hilton & Johnson, 1995b).

The study that focused on light trucks (Hertz et al., 1995a), examined the effects of all-wheel ABS and rear-wheel ABS separately. The findings for the rear-wheel ABS systems showed significant reductions in nonfatal rollovers and side impacts with parked vehicles or fixed objects. All-wheel ABS systems significantly reduced nonfatal rollovers. Though there were benefits for nonfatal crashes, there were no observed significant reductions in fatal crashes for either rear-wheel or all-wheel ABS on light trucks. In fact, there were significant increases in the number of frontal impacts with another motor vehicle in transport for both nonfatal and fatal crashes associated with vehicles equipped with rear-wheel ABS (Hertz et al., 1995a). Since all-wheel ABS had only began appearing on light trucks in 1989 (Kahane & Dang, 2009), there were only a small number of light trucks with all-wheel ABS, which made finding significant differences in crash rates difficult (Hertz et al., 1995a). Unlike the findings from the study on light trucks, the study on passenger cars found a significant reduction in nonfatal impacts with another motor vehicle in transport associated with all-wheel ABS. Passenger cars with all-wheel ABS also showed significant increases in nonfatal frontal impacts and impacts with parked vehicles or fixed objects as well as fatal rollover and fatal side impacts with parked vehicles or fixed objects (Hertz et al., 1995b).

Insurance Institute for Highway Safety (IIHS) conducted a study to investigate differences in crash data between vehicles with and without ABS, but specifically differences between the first-year model vehicles with all-wheel ABS standard and the last model year before becoming equipped with ABS. The vehicles examined were 1991 non-equipped and 1992 ABS-equipped GM cars' and vans' crash data from 1993 to 1995. For comparison purposes, the

GM vehicle group was compared to the larger group of cars and vans from model years 1984 to 1992 before and after being equipped with ABS from crash data ranging from 1986 to 1995. The results of the study showed a significant increase in the percentage of occupants of vehicles with ABS being involved in a fatal crash, where the increase for the 1992 GM vehicle group was 24% and 26% for the larger ABS-equipped group. Similarly, there was a significant increase in the percentage of single-vehicle crashes for both the 1992 GM vehicle group (39%) and the larger ABS equipped group (45%). There were decreases associated with the 1992 GM ABS-equipped vehicles, with a significant 20% reduction in fatalities to other vehicle occupants involved in crashes with ABS-equipped vehicles and a nonsignificant 26% decrease in crashes with nonoccupants, such as pedestrians and bicyclists. The results of the study suggested that ABS does not reduce the likelihood of a fatal crash and additional research was needed to understand the mixed effects (Farmer, Lund, Trempel & Braver, 1996).

After being informed of the increase in run-off-road crashes that resulted in no net overall effect, the advanced notice of proposed rulemaking (ANPRM) indefinitely deferred ABS as a requirement for passenger vehicles on July 12, 1996 (Federal Register Notice 61: 36698). As a result of this initial investigation, NHTSA established a program to understand ABS's role in run-off-road crashes (Kahane, 1994), which was better known as the Light Vehicle Anti-Lock Braking System Research Program (Garrott & Mazzae, 1999).

In 1998, Hertz, Hilton and Johnson published an update to their previous 1995 studies, analyzing crashes of vehicles with ABS. The 1998 update aimed to include crashes with pedestrians as well as narrowing the crashes evaluated from 1995 and 1996. The crash types evaluated were rollovers, side impacts with parked vehicles or fixed objects, frontal impacts with parked vehicles or fixed objects, frontal impacts with another motor vehicle in transport and crashes with pedestrians. The results for passenger cars showed that the changes in the percentage of crashes in the various categories were similar to the changes observed in the 1995 study for all crashes and fatal crashes. The differences between the two studies were in the areas of all frontal impacts with fixed objects on dry road conditions, where the 1995 study showed significant increases (12%) in crashes that were not observed in the 1998 data that showed a significant decrease (13%) in crashes. Though there were increases in the percentage of side impacts with fixed objects, the percentages in the 1995 study (34-40%) were much higher than the increases observed in the 1998 study (7-8%). The only differences identified for fatal crashes were a significant increase in rollovers on wet pavement from the 1995 study compared to a nonsignificant decrease for the 1998 study. For light trucks equipped with rear-wheel ABS, many of the results from the 1995 study overlapped with the 1998 study. For all crashes, the 1995 study showed a significant increase in the number of multi-vehicle crashes, which was not seen in the 1998 study that showed no significant changes. For front impacts with fixed objects, the 1995 study showed no significant changes in crash rates but the 1998 study showed significant decreases (11%). For fatal rear-wheel ABS vehicles, the 1995 study showed significant increases in multi-vehicle crashes, which was only observed in the 1998 study in the wet road condition. The 1998 study showed significant decreases for front impacts with fixed objects, which was not consistent with the nonsignificant changes from the 1995 study. Similarly, for fatal side impacts the 1998 study showed a significant decrease but was not seen in the 1995 nonsignificant results. For light trucks with all-wheel ABS, many of the results were similar between the 1995 and 1998 studies. For all crashes, multivehicle crashes on dry pavement showed a significant increase of 14% for the 1995 study, where the 1998 study showed a 14% decrease in crashes. The only significant difference identified for the fatal crashes was a significant increase in rollovers (97-125%) that was not present in the 1995 study. The differences between the 1995 and 1998 studies for passenger cars with all-wheel ABS, light trucks with rear-wheel ABS and all-wheel ABS are presented in Table 1.

Table 1. Comparison in crash data between Hertz et al. 1995 and Hertz et al.1998 studies on vehicles with ABS.

All crashes	All wheel ABS on passenger cars		Rear wheel ABS on light trucks		All wheel ABS on light trucks	
Crash type	Hertz et al., 1995b	Hertz et al., 1998	Hertz et al., 1995a**	Hertz et al., 1998	Hertz et al., 1995a**	Hertz et al., 1998
Multi-vehicle***			11%*			
• Dry or favorable pavement	-9%*	-18%*	10%*	4%	14%*	-14%*
• Wet or unfavorable pavement	-35%*	-42%*	16%*	-7%	-21%*	-38%*
Pedestrian strikes				-3%		-5%
• Dry or favorable pavement		-10%*		-5%		-1%
• Wet or unfavorable pavement		-30%*		4%		-19%
Primary rollovers	24%*			-41%*	-36%*	-39%*
• Dry or favorable pavement	27%*	-17%*	-46%*	-43%*	-48%*	-36%*
• Wet or unfavorable pavement	14%*	16%	-31%*	-38%*	-29%	-43%*
Front impacts with fixed objects	15%*		-2%	-11%*	-24%*	-26%*
• Dry or favorable pavement	12%*	-13%*	0%	-11%*	-9%	-24%*
• Wet or unfavorable pavement	24%*	2%	-3%	-10%	-38%*	-33%*
Side impacts with fixed objects	36%*	8%*		-20%*	-24%	
• Dry or favorable pavement	34%*	7%	-15%*	-15%*	-2%	14%
• Wet or unfavorable pavement	40%*	8%	-29%*	-29%*	-46%*	-33%*
Fatal crashes	All wheel ABS passenger cars		Rear wheel ABS on light trucks		All wheel ABS on light trucks	
Crash type	Hertz et al., 1995b	Hertz et al., 1998	Hertz et al., 1995a	Hertz et al., 1998	Hertz et al., 1995a	Hertz et al., 1998
Multi-vehicle***			32%*	20%	-16%	19%

• Dry or favorable pavement	-1%	5%	27%*	20%	-10%	31%
• Wet or unfavorable pavement	-35%*	-40%*	48%*	21%*	-37%	-14%
Pedestrian strikes				-3%		
• Dry or favorable pavement		10%		-5%		8%
• Wet or unfavorable pavement		-38%*		5%		-50%
Primary rollovers	60%*	40%*	7%	16%	15%	103%*
• Dry or favorable pavement	54%*	51%	7%	5%	17%	97%*
• Wet or unfavorable pavement	94%*	-14%	8%	89%	4%	125%*
Front impacts with fixed objects	11%	-12%	11%	-23%*	-10%	6%
• Dry or favorable pavement	9%	-11%	10%	-28%*	0%	16%
• Wet or unfavorable pavement	24%	-16%	16%	3%	-70%	-25%
Side impacts with fixed objects	91%*	63%*	9%	-6%	52%	51%
• Dry or favorable pavement	85%*	61%*	1%	-10%	84%	111%
• Wet or unfavorable pavement	107%*	69%*	23%	2%	-67%	-26%

* Statistically significant
** Nonfatal crashes only, not including fatal crashes
*** Multi-vehicle crashes included frontal impacts with another vehicle in transport

2.2.1 NHTSA's Light Vehicle ABS Research Program (1997-2003)

To investigate why ABS equipped vehicles were associated with increased run-off-road crash rates, NHTSA created the Light Vehicle ABS Research Program. Though the findings of the evaluations of ABS are inconclusive as to why there was no net benefit for ABS, multiple hypotheses were created as a result (Garrott & Mazzae, 1999):

1. The vehicles that were first equipped with ABS were often luxury or sporty vehicles not common to the typical US driver. The increase in single vehicle run-off-road

crashes could have been a statistical fluke associated with luxury or sporty vehicles that may not be observed with economy vehicles.

2. ABS hardware and software have changed since the introduction of ABS on vehicles. The first ABS-equipped vehicles may not perform as well as the updated systems, which could enable drivers to avoid run-off-road crashes.
3. ABS may not perform as required in various situations like braking while making a hard turn or on other surfaces like grass, etc. ABS-equipped vehicles may have had worse performance than non-ABS equipped vehicles, causing the increase in run-off-road crashes.
4. The issue could be related to the driver, where when in an emergency braking scenario, the driver may brake and steer. For vehicles without ABS, often the wheels would lock, which resulted in the driver having no steering control of the vehicle. Regardless if the driver gave steering input, the vehicle continued in the direction it was traveling due to the locked wheels. For vehicles with ABS, the driver retained steering control of the vehicle and may make large steering motions in an emergency situation that could have resulted in the increase in run-off-road crashes.
5. Lastly, the increase in run-off-road crashes could have been caused by changes in drivers' behavior. Drivers with ABS-equipped vehicles may have had perceptions that their vehicle has increased braking performance, thus they could drive at increased speeds, which could be excessive for the scenario, resulting in a single-vehicle crash.

In order to investigate these hypotheses, NHTSA created four specific goals. First, to determine if vehicles with newer ABS hardware and software showed increases in single-vehicle crashes. Second, to investigate why the observed increase in crashes only involved a single vehicle as opposed to multiple vehicles. Third, to evaluate if LTVs with four-wheel ABS showed increases in single-vehicle crashes as more LTVs were equipped with four-wheel ABS as opposed to rear-wheel ABS. Fourth, to develop consensus between NHTSA and automotive manufacturers on the findings. The program outlined seven tasks created to meet the goals of the program in determining why there were not positive benefits with the addition of ABS (Garrott & Mazzae, 1999).

2.2.1.1 Task 1: Analysis of the Crash Experience of Vehicle Equipped with All Wheel Antilock Braking Systems (ABS) – A Second Update Including Vehicles with Optional ABS (September, 2000)

The initial crash data evaluations of ABS relied on luxury or sporty vehicles that were uncommon to the typical US driver. Hertz et al. (1998) updated the evaluation to include data from 1995 and 1996, which included more economy vehicles. The study only included vehicles that did not have ABS or ABS was a standard feature. There was a group of vehicles where ABS was an optional feature, thus Task 1 was focused on expanding the number of vehicles with ABS being evaluated by including vehicles where ABS is optional (Hertz, 2000), adding to the previous Hertz et al. (1998) data. The data for vehicles that came standard with ABS was combined with the data from vehicles where ABS was optional. The crash scenarios examined were crashes with pedestrians, rollovers, run-off-road crashes, side-impact crashes, and frontal crashes for both fatal crashes and crashes at all levels of severity (Hertz, 2000).

The results of the study did not uncover any significant changes in overall effect of ABS like previous studies (Hertz et al., 1995a; 1995b; 1998). The results for passenger vehicles showed significant reductions in crashes of all severity for collisions involving a pedestrian (13.2%), rollovers (8.5%), run-off-road crashes (6.0%), and frontal impact crashes (23.4%). There was a 15.8% increase in the number of side-impact crashes of all severities for passenger vehicles. For crashes at all severity levels involving LTVs, there were significant reductions in rollovers (31.2%), run-off-road crashes (11.3%), and frontal impact crashes (8.6%). Like passenger cars, LTVs showed an increase in side-impact crashes (11.5%) for all crash severity levels. For fatal crashes, the only significant result was an increase (106.5%) in LTV rollover crashes.

When comparing the results of the Hertz (2000) study to the pervious Hertz et al., (1998) study, there were a few differences, but the majority of the results were similar (see Table 2). For passenger cars, the 1998 results showed significant increases in fatal rollovers and side impacts with fixed objects, though the 2000 study results also showed increases that were not significant. For LTVs, the majority of the results were similar between the two studies, especially the significant increase in the percentage of rollovers (Hertz et al., 1998; Hertz, 2000).

Table 2. Comparison in crash data between Hertz et al., 1998 and Hertz et al., 2000 studies on vehicles with ABS.

All crashes	All wheel ABS on passenger cars		All wheel ABS on LTVs	
Crash type	Hertz et al., 1998	Hertz, 2000	Hertz et al., 1998	Hertz, 2000
Pedestrian strikes		-13.2%*	-5%	-2.6%
• Dry or favorable pavement	-10%*		-1%	
• Wet or unfavorable pavement	-30%*		-19%	
Primary rollovers		-8.5%*	-39%*	-31.2%*
• Dry or favorable pavement	-17%*		-36%*	
• Wet or unfavorable pavement	16%		-43%*	
Front impacts with fixed objects		-23.4%*	-26%*	-8.6%*
• Dry or favorable pavement	-13%*		-24%*	
• Wet or unfavorable pavement	2%		-33%*	
Side impacts with fixed objects	8%*	15.2%*		11.5%
• Dry or favorable pavement	7%		14%	

• Wet or unfavorable pavement	8%		-33%*	
Fatal crashes	All wheel ABS passenger cars		All wheel ABS on LTVs	
Crash type	Hertz et al., 1998	Hertz, 2000	Hertz et al., 1998	Hertz, 2000
Pedestrian strikes		-0.4%		-22.7%
• Dry or favorable pavement	10%		8%	
• Wet or unfavorable pavement	-38%*		-50%	
Primary rollovers	40%*	12.3%	103%*	106.5%*
• Dry or favorable pavement	51%		97%*	
• Wet or unfavorable pavement	-14%		125%*	
Front impacts with fixed objects	-12%	-4.9%	6%	17.9%
• Dry or favorable pavement	-11%		16%	
• Wet or unfavorable pavement	-16%		-25%	
Side impacts with fixed objects	63%*	32.4%	51%	-0.3%
• Dry or favorable pavement	61%*		111%	
• Wet or unfavorable pavement	69%*		-26%	

* Statistically significant

The results of Task 1 continued to show the obscure increases and decreases in various types of crashes, even with the increased number of vehicles with ABS included in this study. The results showed the significant increase in rollover crashes for LTVs (Hettz, 2000), which was consistent with the findings from Hertz et al., 1998. The only statistically significant increase identified in passenger vehicles was for side impacts with fixed objects over all crash severity levels. The majority of the remaining crash scenarios examined showed significant decreases for crashes of all severity levels combined. Interestingly, crashes involving rollovers or side impacts with fixed objects could be attributed to the driver losing control of the vehicle, but ABS was expected to help drivers remain in control by increasing directional stability (Hertz et al., 1998).

2.2.1.2 Task 2: National Telephone Survey of Driver Experiences and Expectations Regarding Conventional Brakes versus ABS (November, 2001)

Task 2 was a national phone survey centered around experience and expectations of ABS. The survey aimed to understand if operating ABS or drivers' beliefs of the capabilities of ABS from both individuals that owned vehicles with ABS and those without, could change the overall effectiveness. The survey was administered in both English and Spanish to 145,535 US households over a four-month period in 1999. Households were selected using the Random Digit Dialing method, where numbers were randomly selected using a set of known US phone number prefixes. Participants needed to be drivers over the age of 16, that had driven a vehicle within the last year. If there was more than one eligible driver in the household, the person with the nearest birthday was selected. There was a total of 3,508 participants in this study. The participant sample consisted of 46.5% males and 53.5% females. The largest age group was aged 30-60 (46%), followed by participants over the age of 60 (20%), then by those aged 26-35 (17%) and finally those under the age of 26 (15% [Mazzae, Garrott & Snyder, 2001]).

The results of the survey found that only 38.8% of the participants knew that ABS stood for anti-lock brake system, where approximately half of the male participants were correctly able to identify what ABS stood for. Eighty-seven percent of participants had heard of the anti-lock brake system. When asked what the advantages of ABS were, 39.2% reported that ABS prevents wheel lockup and the resulting skidding. The majority of participants did not know of any or thought there were no disadvantages associated with ABS. When asked when ABS activates, 31% responded when ABS senses a skid, 22% said when hard pressure is applied to the brake, and 21% said as soon as the brake is used. In order to brake in the shortest distance possible with a vehicle equipped with ABS, 48% of participants said to apply light brake pressure, 28% said to push the brake as hard as possible and 16% said to pump the brake. For drivers that had vehicles equipped with ABS, 57.8% of participants had felt ABS activation, where 91.8% of the participants that reported activating ABS on their vehicle identified correct reasoning as to their experience feeling or hearing ABS activate. Of the participants that had not activated on ABS on their ABS-equipped vehicle, they were asked if they had ever activated ABS on any vehicle and 26% of the participants reported activating ABS on any vehicle they were driving. For brake pedal feedback associated with ABS, 46% of participants thought there would be something wrong with the vehicle if the pedal was to vibrate and 34% thought the vibration was normal for ABS activation. Only 30% of the participants knew to maintain pedal pressure when ABS activates, and the pedal vibrates. At the time of the study, some brake pedals would either drop to the floor or would push back against the driver's foot during ABS activation. If the pedal were to drop to the floor, 45% of the participants thought they should pump the pedal and 25% would take their foot off the pedal. If the pedal pushed against the driver's foot, 31% identified that ABS was activating, but 30% of participants thought there would be a brake malfunction. Only 20% of participants knew that a clicking or ratcheting noise during emergency braking was associated with ABS activation and 41% thought the noise meant there was a brake malfunction. Forty-seven percent of participants reported that their personal vehicle was equipped with ABS, where roughly half of the vehicles on the road had ABS. For participants that had ABS on their personal vehicle, 38% were startled by the brake pedal feel during an emergency stop. During the stop, 51% reported feeling the pedal vibrating or pumping, 21% felt a stiff or hard to press pedal and 11% heard a noise. In response to the brake pedal feel, 48% reported taking their foot off the pedal (Mazzae, Garrott & Snyder, 2001).

As part of the survey, drivers were asked questions that targeted behavioral adaptation to ABS, where drivers may have altered their behavior through increased risk taking based on the driver's assumptions of added safety from ABS and/or from the driver's knowledge of ABS.

Participants were asked if they would be more likely to drive faster and pass another vehicle on dry, wet, snow-covered, and icy roads if the vehicle they were driving were equipped with ABS. For the participants who reported that they would be more likely to drive on all of the wet, snow-covered or icy roads with a vehicle with ABS, they were more likely to report that ABS allowed them to avoid an unavoidable crash. This was also true for those who would speed or pass other vehicles in dry and wet road conditions. Though NHTSA did not find evidence of different driving behaviors between drivers with vehicles equipped and not equipped with ABS, the authors claim the risky behaviors identified by the survey could be due to the survey itself. Possible issues with the survey could have been the question order, survey length, and that participants were asked what they thought their behavior would be (Mazzae, Garrott & Snyder, 2001).

Fifty-six percent of the participants had purchased a new vehicle, where 50% of new vehicle purchases were between 1995 and 1999. When shopping for their new vehicle, 37% of participants discussed ABS with an employee at the dealership. For those who purchased a new vehicle, 27% received information on ABS, where participants were either given or shown an owner’s manual (58%), ABS brochure (45%) or a safety feature brochure (17%). Participants were asked if they heard it was a good idea to practice braking with ABS in a non-emergency situation when they purchased their vehicle. Only 32% heard it was a good idea to practice and 31% reported trying out ABS in a non-emergency situation. Participants were also asked about education and practice with ABS during the next time they were purchasing a vehicle with ABS. The education and practice options ranged from 10 to 30 minutes and included reading instructions, listening to an audiotape, watching a video, practicing on a simulator and practicing in the vehicle. The most preferred options were a 10-minute video on how ABS works and 15 minutes of practice on an ABS simulator (Mazzae, Garrott & Snyder, 2001).

The survey results did show trends related to gender, age, education level and income. Generally, when it came to an understanding of ABS males knew more than females, younger drivers knew more than older drivers, individuals with higher levels of education knew more about ABS than those with less education, and drivers with a higher income knew more than those with lower income levels. These trends may have been influenced by the type of customer who was willing to purchase a vehicle with ABS and gained experience through driving an ABS-equipped vehicle. Participants that did not drive ABS-equipped vehicles were less likely to know the sound and feel characteristics associated with ABS activation. The overall results of the survey study showed that many drivers lacked knowledge of what ABS does, how it affects performance, when it activates, and if their personal vehicle was equipped with ABS. The survey revealed that the lack of knowledge of ABS could lead to dangerous reactions to the feedback from ABS when activated (Mazzae, Garrott & Snyder, 2001).

2.2.1.3 Task 3: Study NASS Hardcopy Crash Files to Determine Typical Single-Vehicle Crashes for ABS-Equipped Vehicles

Task 3 sought to examine the National Automotive Sampling System’s hardcopy files to determine if crashes from vehicles equipped with ABS were due to a brake performance issue or another operational issue, like falling asleep and departing the road (as cited in Garrott & Mazzae, 1999). Though Task 3’s report was never published, the results of the study were summarized in later tasks. A total of 257 single-vehicle crashes from 1996 for vehicles with and without ABS were examined. The results of the study were inconclusive, showing no significant effects of ABS on crash rates (Mazzae, Barickman, Forkenbrock & Baldwin, 2003).

2.2.1.4 Task 4: A Test Track Study of Light Vehicle ABS Performance Over a Broad Range of Surfaces and Maneuvers (January, 1999)

Task 4 of the Light Vehicle ABS Research Program aimed to determine if there were performance issues with the ABS system through testing on various road surfaces and vehicle maneuvers. Though NHTSA conducted two previous studies on ABS performance on various road surfaces and vehicle maneuvers (Hiltner, Arehart & Radlinski, 1991; Arehart, Radlinski & Hiltner, 1992), there were multiple reasons for an updated study. The vehicles included in the initial studies were equipped with the first ABS systems from the late 1980s to very early 1990s. As time progressed, high production passenger vehicles were equipped with ABS from the mid to late 1990s. Task 4 aimed to expand the number of surfaces, especially in conditions where there was a sudden change in the coefficient of friction (traction), which had been shown to cause issues in the previous 1991 and 1992 studies. In addition to expanding the road surfaces tested, there were also maneuvers added to further investigate areas of deficiency from the 1991 and 1992 studies (Forkenbrock, Flick, & Garrott, 1999).

Nine different high-volume vehicles ranging from cars to LTVs with ABS were selected for the study. Each vehicle was tested with ABS enabled and then with ABS disabled. Vehicles were tested in a light and heavy loading condition. In the light load test condition, the load consisted of a full tank of gas, weight of the driver and instrumentation. The heavy load condition was set to the manufacturer recommended Gross Vehicle Weight Rating (GVWR), which is the maximum load recommended by the manufacturer for each vehicle, this was achieved using sandbags distributed thought the vehicle. Nine different surface conditions were tested, including: dry asphalt, wet asphalt, dry concrete, wet polished concrete, wet epoxy, grass, loose gravel, wet Jennite, and epoxy/sand. The braking maneuvers included in the study included: straight line braking, braking around curves, J-turns and a single lane change. A total of 18 conditions were tested based on a combination of surfaces and maneuvers, including transitions (sudden changes in the coefficient of friction / traction) and split mu (different coefficients of friction / traction between the right and left sides of the lane). One professional driver was used to test all vehicles in all conditions, and in addition, used two different brake application techniques. The panic technique was a rapid application of the brake pedal when ABS was enabled and disabled, which was over the minimum 667 N force and was repeatable. The other technique used when ABS was disabled was called “best effort”, where the driver modulated brake pedal pressure in order to stop in the shortest distance without allowing more than one wheel to lock per axel to retain directional stability. Since steering control was lost when a vehicle’s wheels were locked, the “best effort” technique was not tested for conditions involving steering (Forkenbrock, Flick, & Garrott, 1999).

The results of the study showed that when ABS was enabled, vehicles stopped in shorter distances and retained better directional stability than when ABS was disabled in almost all conditions, especially the wet or slippery conditions. The conditions where ABS was disabled that showed shorter stopping distances than when ABS was enabled included: grass for the light load condition (7.1% increase) and loose gravel for the light and heavy load conditions (27.2% increase for both loading conditions). Though ABS was not effective in all conditions, Task 3 revealed that many of the crashes occurred on dry paved roads, which ABS showed to be effective in reducing the stopping distance compared to when ABS was disabled. This conclusion led the authors to believe that there were not performance deficiencies associated with ABS that were causing the increase in single-vehicle run-off-the-road crashes (Forkenbrock, Flick, & Garrott, 1999).

During this study, the professional test driver observed different cues from the feel and sound of ABS during the different driving conditions. Surfaces with a very low coefficient of friction (slippery) like epoxy, ABS's feel, and sound was much more pronounced in some vehicles, which could have startled a driver that was unfamiliar with ABS or a driver who did not expect ABS to activate. A startled driver may have taken their foot off of the brake pedal or release some of the pressure on the brake pedal, which would increase the distance the vehicle needs to stop. As a result, the authors encouraged drivers to practice activating ABS under various surface conditions and maneuvers (Forkenbrock, Flick, & Garrott, 1999).

Though Task 4 was essentially an update to previous NHTSA studies (Hiltner, Arehart &Radlinski, 1991; Arehart, Radlinski & Hiltner, 1992), the study showed evidence that the performance of the system itself was not causing the increases in run-off-road crashes. The authors hypothesized that varying feedback from different conditions in combination with inexperienced or unsuspecting drivers could have contributed to the increases in crashes. The biggest takeaway from this study was the recommendation for drivers to practice activating ABS under various conditions (Forkenbrock, Flick, & Garrott, 1999). The authors acknowledged that without practice or training, ABS was not intuitive to drivers and could cause potentially dangerous reactions that could be contributing to the increase in crashes.

2.2.1.5 Task 5 Part 1: Examination of Drivers' Collision Avoidance Behavior Using Conventional and Antilock Brake Systems on the Iowa Driving Simulator (August, 2000)

Previous tasks had shown that there were no significant performance deficiencies associated with ABS, but there continued to be an increase in single-vehicle run-off-road crashes for vehicles equipped with ABS, especially rollovers. Task 5 part 1 aimed to investigate drivers' crash avoidance behavior in a crash-imminent situation to see if there were any connections to run-off-road crashes. One of the hypotheses surrounding why there was an increase in crashes for vehicles with ABS was that drivers oversteer in an obstacle avoidance scenario. Prior to the introduction of ABS, during heavy braking the wheels could lock up, causing the loss of steering control of the vehicle. Regardless of the drivers steering input, the vehicle continued in the direction it was moving. Since drivers retain steering control during hard braking with ABS, it was hypothesized that drivers were oversteering in an emergency situation but were then running off the road because they had steering control that they previously did not. Task 5 part 1 explored this hypothesis through a crash-imminent situation where drivers must make evasive maneuvers to avoid a collision with another vehicle using the National Advanced Driving Simulator (NADS) (McGehee et al., 2000).

Researchers utilized NADS's full vehicle driving simulator fitted with ABS to allow for a crash-imminent scenario in the safe simulation environment. The simulator included four cameras to capture the driver's reaction and to confirm the simulator data. The scenario placed participants in a crash-imminent scenario in an intersection, where another vehicle entered the lane the driver's vehicle was traveling in, which caused the driver to make an evasive maneuver to avoid the encroaching vehicle. The study consisted of 120 participants, with 60 males and 60 females, ranging from 25 to 55 years old. Participants were required to have a valid driver's license, pass the University of Iowa's health screening for the simulator and not have participated in previous simulator research at the university. The between-subjects factors evaluated were brake system, speed limit, time-to-intersection (TTI) and instruction type. The two brake systems being evaluated were a conventional brake system and ABS. Two different speeds, 45 and 55mph, were evaluated to see if behavior changed with speed. TTI was the time for the driver to reach the intersection that would start the incursion event, which was either 2.5 or 3.0 seconds, to see if the driver's avoidance strategy changed with more or less time before the event. For instructions, there were two groups, one received the simulator safety video and the other saw the simulator safety video as well as an ABS specific video. The ABS instructional video was taken from General Motors, which was designed for customers who purchased a new vehicle with ABS. The video explained the benefits of ABS by showing the differences between a locked and unlocked wheel during hard braking with and without steering input. The video demonstrated proper driver operation of ABS including the expected feedback from the brake pedal and the sound. A description of the major components of ABS and service needs based on the dashboard warning lights were also included (General Motors, 1994). There was a total of 80 participants in the ABS brake system condition and 40 in the conventional brake condition. All participants in the conventional brake system condition and 40 of the 80 participants in the ABS condition only viewed the simulator safety video. The other 40 participants in the ABS condition watched both the simulator safety video and the ABS specific video (McGehee et al., 2000).

In order to lessen the suspicion of an intersection incursion event, participants were informed they would be driving for 30 minutes when they were really only driving for 15 minutes. Once the participant was fit into the simulator, they were given a 5-mile practice portion on a rural two-lane road to get familiar with the steering and pedals before data collection began. Once data collection began at the 5-mile mark, participants continued to drive on the rural two-lane road. At mile 7, the participants encountered a slow-moving tractor trailer, which was unable to be passed due to perfectly timed oncoming traffic. The tractor trailer went over a hill, slowing down to 25mph and pulled over to the shoulder once over the hill. After the tractor trailer had been passed, there was a lead vehicle that maintained a six second headway, leading the participant through the upcoming intersection. The purpose of the lead vehicle was to encourage participants to feel there was no need to slow down at the intersection because the lead vehicle easily passed through the intersection without slowing down. The intersection where the incursion took place was the only intersection on the route. The intersection consisted of a light truck at a stop sign on the perpendicular road to the left of the participant and a Buick Regal that was positioned 48.5ft away from the stop sign on the right side of the intersecting road. When the participant was within either 2.5 or 3.0 seconds away from the intersection, depending on which condition they were in, the incursion vehicle accelerated and stopped 6ft in the participants lane (see Figure 9 [McGehee et al., 2000]).

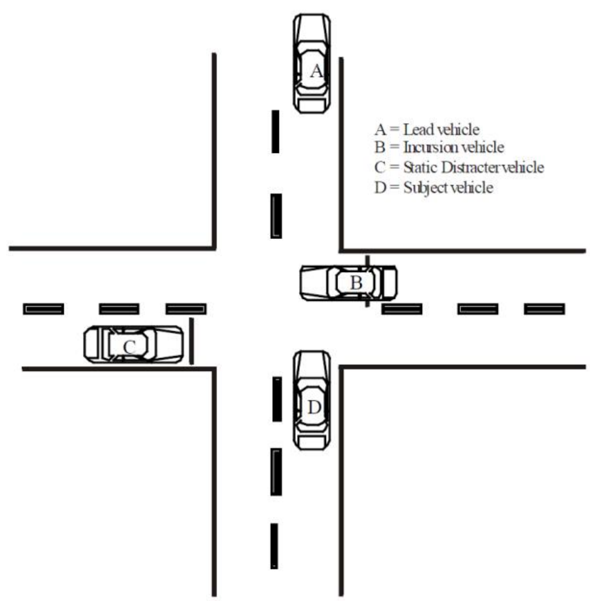


Figure 9. Intersection incursion where vehicle B enters the participant's lane (vehicle D [McGehee et al., 2000])

The encroaching Buick Regal required the driver to make an evasive maneuver to avoid a collision. There was no oncoming traffic or other moving traffic that the participant encountered during the intersection incursion, which gave the participant enough space to avoid the encroaching Buick Regal to the left or right. After making the evasive maneuver, the participant did not encounter any other incursion events and the driving portion of the study was over. The participant then completed a post-driving survey to gain feedback on the simulator and scenario (McGehee et al., 2000).

The analysis of the study was broken out into three categories of dependent variables, which included: initial response, emergency braking and steering measures, and the final outcome. The initial response category included variables such as the time-to-accelerator-release, time-to-brake-press, time-to-first-steering and transitional times between these actions. The emergency braking and steering measures were associated with the drivers crash avoidance strategy to either brake, steer or a combination of both. Lastly, the outcome category examined the road departures and crashes. The analysis examined the three categories of dependent variables while also examined the differences between the four independent variables, brake system, speed limit, time to the intersection, and instruction type (McGehee et al., 2000).

The results showed that the crash avoidance strategy used by all 120 was a combination of braking and steering, where 79% applied the brakes first, 17% steered first, and 4% braked and steered simultaneously. The majority (96%) of participants either locked the wheels with conventional brakes or activated ABS if their vehicle was equipped. The initial steering input direction favored the left (60%) over the right (40%), which was also the case for the avoidance steering input, where steering left (86%) was much more common than steering right (17%). Thirty-five percent of the drivers crashed into the incursion vehicle, where 35.9% the participants that steered left crashed, and 29.4% of the participants that steered right crashed. There was a total of eight participants that departed the road, where six made severe steering inputs and four made severe enough inputs to spin off the road (McGehee et al., 2000).

The results for the effects of the conventional brake system versus ABS, did not show significant differences for the initial response variables. Since these variables depended on the driver's behavioral response to the incursion vehicle, the brake system was not involved yet, nor should it have had an effect. For the emergency braking and steering response category, there was more severe steering input observed from the drivers with conventional brakes compared to the drivers with ABS. The maximum steering input, maximum steering range, and maximum steering rate were all higher for drivers with the conventional brake system. The drivers with conventional brakes took more time to move the steering wheel to the maximum input in comparison to the drivers with ABS. For braking behavior, brake pedal depression duration was significantly longer, maximum brake force was higher, and the time to depress the pedal to the maximum force was shorter for drivers with conventional brakes compared to drivers with ABS. Interestingly, for the eight participants that departed the road, four had conventional brakes and four had ABS. There were also six two-wheel partial road departures, where five had conventional brakes and only one had ABS. Of the 35% of drivers that collided with the incursion vehicle, drivers with ABS crashed less frequently (31%) than drivers with conventional brakes (43%), but this difference was not significant. The results of the logistic regression showed that brake system did have a significant effect. Between the two systems, ABS showed increased stability and control (McGehee et al., 2000).

There was a total of 40 participants that received the ABS specific instruction in addition to the simulator safety instruction, 40 participants within the ABS brake system group that received the simulator safety instruction and 40 participants in the conventional brake system group that received the simulator safety instruction. There were no significant differences between the group that received ABS specific instruction and the groups that received the simulator safety training for the initial responses, emergency braking and steering responses, or outcomes. The only difference observed was the impact speed, where the participants that had received the ABS, specific instruction had higher mean speed (32.5mph) than the participants that received the simulator safety instruction only (27.5mph mean speed), but this difference was not significant. The study did find that none of the participants released the brake pedal when they felt the vibration from ABS activating. The questionnaire did not find any major anomalies between the ABS and the conventional brake system groups. Participants were asked if they had previously activated ABS and if their vehicle has ABS, but the results were not included in this report (McGehee et al., 2000).

The incursion vehicle accelerated when the participants were either 2.5 or 3.0 seconds away from the intersection, representing two different TTI values to investigate possible changes in behavior. Previous research had shown that the further away the driver was from the crash scenario the more brake input they used, but the closer the driver became to the crash scenario, the more steering input was added. Interestingly, the shorter 2.5 second TTI resulted in slower initial release of the accelerator pedal, longer time to apply the brake, but a faster time to first steering action, when compared to those in the 3.0 second TTI group. Though there were no significant differences in the emergency steering behavior, the 2.5 second TTI group did depress the brake pedal in a shorter time than the 3.0 second TTI group. TTI was found to have a strong effect on the outcome of the incursion event, where only 10% of participants in the 3.0 second TTI group crashed, but 60% of participants in the 2.5 second TTI group crashed. These observations may suggest that there is a point of no return, where drivers commit to an action, which in this case, may be that the incursion vehicle would not enter into their lane causing a collision (McGehee et al., 2000).

Participants were also divided into two different speed limit groups, where one group's goal was to drive at 45mph and the other at 55mph. There were no effects on the initial responses or emergency braking and steering behavior based on speed. There was a total of eight road departures, where four were in the 45mph speed limit condition (all in ABS group), and four were in the 55mph speed limit condition (all in conventional brakes group). For the crash outcome, 28% were observed in the 45mph speed limit group and 42% were in the 55mph condition. Interestingly, there were almost an even percentage of crashes between conventional brake systems and ABS in the 55mph condition, but only 22% of the 45mph crashes were attributed to ABS and 40% to the drivers with conventional brakes (McGehee et al., 2000).

The general results of this study showed that there were no significant oversteering effects linked to vehicles equipped with ABS when using a high-fidelity driving simulator. The drivers in the ABS group showed more stability and control during the incursion event than those with conventional brakes. In the emergency avoidance event, all 120 participants used a combination of braking and steering to attempt to avoid the incursion vehicle. The majority of the participants' first response was to brake and then as they moved closer to the encroaching vehicle, steer away from the vehicle (McGehee et al., 2000).

2.2.1.6 Task 5 Parts 2 / 3: Test Track Examination of Drivers' Collision Avoidance Behavior Using Conventional and Antilock Brakes (March, 2003)

The goal of Task 5 was to examine driver crash avoidance behavior. Subtask 5.1 explored crash avoidance behavior using a simulator, where subtasks 5.2 / 5.3 utilized a test track for dry (5.2) and wet (5.3) pavement conditions. The same intersection incursion scenario from subtask 5.1 was used for subtasks 5.2 / 5.3, where an incursion vehicle moved into the lane the participant was traveling in from the participant's right, prompting the collision avoidance behavior. This study looked at the differences in behavior based on the amount of time the driver had to react to the incursion vehicle, brake system, the level of ABS brake pedal feedback, gender, viewing an instructional video on ABS and a practice braking task before the test scenario. The incursion vehicle began moving when the participant's vehicle was either 2.5 or 3.0 seconds away from the intersection to see if the drivers' behavior changed based on the time available to react. Two different vehicles were used for this study, a Chevrolet Lumina and a Ford Taurus. Both vehicles were equipped with ABS, but some participants experienced ABS and others drove with ABS disabled to represent a conventional braking system. These two vehicles were equipped with ABS from different suppliers, which is why the vehicles had different levels of feedback when ABS was activated. The Chevrolet Lumina had lighter feedback than the Ford Taurus, which had a heavy amount of feedback. Like subtask 5.1, some of the participants in the ABS condition were shown General Motors instructional video on ABS intended for an individual purchasing a vehicle with ABS (General Motors, 1994). Subtask 5.2 included a subset of participants in both the ABS and conventional brake system groups in a practice braking task prior to the test scenario. The braking practice consisted of three trials where the participant drove straight and approached a cone in the middle of their lane. Participants were told to avoid the cone at a certain point, but not given any instruction of how to do so. The purpose was to allow participants that had never experienced ABS to feel the feedback and the capabilities of the vehicle. The braking practice took place on a wet Jennite-pad to replicate wet driving conditions where the road has a lower coefficient of friction. The braking practice was not included in subtask 5.3 because the Jennite-pad was located at the intersection of the test scenario to emulate wet conditions. Since the study took place on a closed-road track, the straight rural drive used in subtask 5.1 with the simulator was not able to be used for 5.2 / 5.3. The test track featured a figure eight course where the intersection was created inside one of the loops. The intersection had stop signs on the perpendicular road to stop cross traffic, but there was no stop sign on the road the participant was traveling on. At the stop signs there were two stopped vehicles on the perpendicular road, one to the left and to the right (Mazzae, Barickman, Forkenbrock, & Baldwin, 2003).

A total of 192 participants in the dry pavement study (5.2) and 54 participants in the wet pavement study (5.3), were all between 25 and 55 years old. Researchers tried to recruit participants that did not have ABS on their primary vehicle and/or never activated ABS previously to see if the brake pedal feedback during ABS would cause adverse reactions. In order to gain participants' realistic reactions to a crash-imminent situation, the participants had to remain unaware of the planned incursion scenario. Participants were told the goal of the study was to focus on driver behavior when steering and maintaining speed in typical driving conditions. The study was supposed to last 30 minutes, but the incursion event happened approximately 15 minutes into the drive. Once in the vehicle, participants listened to audio instructions that gave an overview of the drive. If the participant was part of the braking practice, they would perform the three practice trials before the test drive began. Directly before the test drive began, a lead vehicle passed the participant's vehicle. The lead vehicle was driven by a professional driver, but the participants were told it was another participant. After the first lap, the participant was instructed to use the “laser rangefinder” to monitor the distance between their vehicle and the lead vehicle, which needed to be 200 feet. Monitoring the distance between the vehicles helped the driver to maintain their speed, which was either 45mph in the dry pavement study or 35mph in the wet pavement study. After the participant passed through the intersection a second time, study personnel entered the two parked vehicles to act like drivers as the participant passed through the intersection a third time. After the third pass through, the study personnel set up the vehicle-like polystyrene vehicles in place of the real vehicles, moving the real vehicles out of the intersection. Polystyrene vehicle representations were used to keep drivers from hitting another actual vehicle and keep everyone safe. The encroaching vehicle, a Dodge Neon vehicle representation, was placed onto cable guides, which were attached to another vehicle parked 200ft away. During the fourth pass through by the driver, once the participant’s vehicle touched the marked line, the driver parked 200ft away would accelerate, towing the Dodge Neon vehicle representation 6ft into the participant’s lane. Once the incursion event happened, the driving portion of the study was complete. Participants then filled out a questionnaire to understand their thoughts on the incursion scenario as well as gain information about their driving experience and background (Mazzae et al., 2003).

During the test scenario, the participant’s vehicle was equipped with instrumentation to capture the participant’s braking and steering inputs, as well as the vehicle motion. In order to determine if ABS was activated, a combination of brake line pressure, brake pedal force, individual wheel speed and vehicle travel speed were utilized. When ABS was activated, the brake line pressure showed a dip followed by a build in pressure, while the force applied to the brake pedal was constant. ABS activation was also confirmed through wheel speed, where momentarily slip followed by recovery was observed on one or more wheels. Wheel lockup was determined by looking at individual wheel speed and vehicle speed, where a locked wheel would have a speed approaching zero, but the vehicle speed was above zero (Mazzae et al., 2003).

The results of the study showed that the majority of the participants both braked and steered during the incursion scenario. The distribution of participants that braked versus steered first was nearly evenly split between the two actions. There were more participants that steered to the left than right. Though there were no major differences in braking behavior between the dry and wet pavement studies, there were larger steering inputs observed in the wet pavement study compared to the dry pavement study. Interestingly, 27% of participants in the dry pavement study missed pressing the brake pedal once but only 8% in the wet pavement study missed pressing the brake pedal. There were two participants that experienced full four-wheel road departures during the dry pavement study. Three participants had partial road departures where one or two of the vehicle's wheels left the road. Two of the partial road departure participants were in the dry pavement study and one was part of the wet pavement study. Participants in the wet pavement study were much more likely (71%) to crash than those in the dry pavement study (39%, [Mazzae et al., 2003]).

To investigate differences in behavior, some participants drove with ABS enabled (128 dry pavement study participants and 36 wet pavement study participants) and others drove vehicles with ABS disabled to represent vehicles with conventional brakes (64 dry pavement study participants and 17 wet pavement study participants). The major differences observed between the participants that drove vehicles with ABS versus conventional brakes was drivers' steering behavior. Generally, more steering input and longer times to make steering inputs was observed from the conventional participants than those with ABS. The increased steering input associated with conventional brakes was more exaggerated in the wet pavement study than the dry pavement study. The two participants with full four-wheel road departures were driving vehicles with ABS, where one participant activated ABS and the other did not. Researchers did not believe that ABS was a contributing factor to why the two participants in the dry pavement condition had full road departures. Only one of the three participants that experienced a partial road departure had a vehicle with ABS. For crashes with the incursion vehicle, ABS resulted in a significantly lower percentage of crashes (58%) compared to those with conventional brakes, where all participants in the wet condition with conventional brakes crashed (Mazzae et al., 2003).

The two vehicles' participants drove were the Chevrolet Lumina that represented light ABS brake pedal feedback and the Ford Taurus representing heavy ABS brake pedal feedback. There were differences in performance between these two vehicles, where the Lumina had higher deceleration rates in the dry pavement study compared to the Taurus. Drivers of the Taurus did not press the brake pedal as long as those in the Lumina for all brake system conditions. In the dry pavement study, Taurus drivers took less time to press the brake to the maximum position (maximum position driver pressed the pedal to). Taurus drivers in the dry pavement study also had significantly fewer ABS activations and wheel lockups in the conventional brake system condition, compared to the Lumina. Interestingly, the dry pavement study showed that significantly more participants driving the Taurus with the heavy ABS feedback crashed significantly more (64%) than those in the Lumina with a lower level of ABS feedback (27%). Though drivers of the Taurus in the dry pavement study pressed the brake pedal faster, the increase in speed to depress the brake pedal over drivers of the Lumina, may be due to the Taurus drivers not depressing the brake pedal as far as the Lumina drivers. Not pressing the brake pedal as far would result in fewer cases of ABS activation and wheel lockup, which was consistent with observations of the participants driving the Taurus. The crash results for the wet study are opposite of the dry study, where 72% of participants driving the Lumina with light ABS feedback crashed compared to only 44% of Taurus drivers. Though these appear to be large differences, neither are statistically significant (Mazzae et al., 2003).

Half of the participants in the ABS group for both the dry and wet pavement studies watched an ABS instructional video. The results of this instruction did not show a significant effect on braking performance, either by activating ABS or avoiding the incursion vehicle. The only differences observed were longer brake pedal applications in the dry pavement study and faster transition time from the gas to brake pedal in the wet pavement study for participants that watched the ABS instructional video. A total of 64 participants in the ABS group and 32 in the conventional brake system group were given three braking practice trials before the test scenario. The braking practice, like the ABS instructional video, did not produce any differences in performance, including activating ABS or locking conventional brakes or crashing into the incursion vehicle. The interaction between braking practice and ABS instruction was investigated to find that the participants with ABS with braking practice but no ABS instruction crashed 25% of the time compared to the 50% that crashed in the conventional brake system group in the dry pavement study (Mazzae et al., 2003).

For the two different TTI increments, that represent the time the participant was from the intersection when the incursion vehicle began moving, there were differences in driver behavior. The steering behavior observed in the 2.5 second TTI was much faster and involved more steering movements than those in the 3.0 second TTI. Similarly, the braking behavior was much faster and there were higher brake pedal forces associated with the 2.5 second TTI. In the dry pavement study 51% of participants in the 2.5 second TTI condition crashed, but only 29% of participants in the 3.0 second TTI condition crashed. For the 2.5 second TTI condition, though nearly half of the participants in the dry pavement study crashed, 72% of participants crashed in the wet pavement study (Mazzae et al., 2003).

There was a total of 104 males and 88 females in the dry pavement study as well as 26 males and 27 females in the wet pavement study. There were no significant differences between males and females in crash avoidance behavior or resulting crashes. There were some instances of higher steering and braking inputs, but those did not affect the overall outcome of crashes. The interaction between gender and brake system was examined. The results showed that males crashed significantly less with ABS on wet pavement (63%) than with conventional brakes (100%). Similarly, females also crashed significantly less with ABS on wet pavement (55%) than with conventional brakes (100%, [Mazzae et al., 2003]).

After the incursion scenario ended, the participants completed a survey on their experience and background. The results of the survey showed that the participants thought the incursion scenario was realistic enough to gain genuine crash avoidance behavior. The survey revealed that 19% of participants in the dry pavement study and 26% of participants in the wet pavement study had ABS on their primary vehicle even though they had tried not to recruit those participants. Seventy percent of participants in the dry pavement study and 68% in the wet pavement study had previously experienced locked vehicle wheels and skidding. Interestingly, 40% of the participants had previously experienced problems trying to abruptly stop. In fact, 35% of dry pavement study participants and 31% of wet pavement study participants reported having to leave the roadway to avoid a collision, which was primarily attributed to other vehicles or animals on dry pavement. The survey also asked participants about their understanding and previous use of ABS. When asked if they knew what the acronym ABS stood for, 63% of participants in the dry pavement study and 64% of participants in the wet pavement study knew that ABS stood for anti-lock braking system. This percentage may have been inflated because 34% of participants in both studies were shown the ABS instructional video that explained what ABS stood for. Only 22% of participants in the dry pavement study and 30% of participants in the wet pavement study had ever activated ABS. Interestingly, the majority of the participants in both studies reported that ABS wasn't activated during the incursion scenario, but the results show that 46% of all participants activated ABS (32% dry pavement study and 97% wet pavement study). The study's researchers believed many of the participants did not know what to look for when ABS was activated based on the percentage of participants that did not know what ABS stood for (Mazzae et al., 2003).

The results of the study suggest that the drivers did not tend to oversteer in a crash-imminent intersection scenario. Almost all participants in the dry and wet pavement studies used a combination of braking and steering to either avoid or attempt to avoid the incursion vehicle. ABS showed significant benefits over conventional brakes in the wet pavement study, but these benefits were not observed in the dry pavement study. There was no evidence of ABS brake pedal feedback startling drivers or drivers removing their foot from the brake pedal in either study or level of feedback. The results suggest that there were not any current issues with ABS and crash avoidance behavior that would contribute to single-vehicle run-off-road crashes. There was no evidence that the ABS video instruction or braking practice had any effect on crash avoidance behavior. The researchers did acknowledge that these studies were one example of driver crash avoidance behavior, and the results may not extend to other scenarios or higher speeds (Mazzae et al., 2003).

2.2.1.7 Task 6: Test the Effects of ABS When Performing a Two-Wheel Road Recovery Maneuver

Task 6 explored the effects of ABS on road recovery maneuvers, like returning the vehicle to the road after a departure. Road departures can occur for a variety of reason ranging from driver inattention to sleepiness to intoxication, where the driver continues on a straight path off the road. Though Task 6's report was never published, the results of the study were summarized in other task reports. The results concluded that the causes of these kinds of road departures are not attributed to ABS, but the study was inconclusive if ABS had an effect on the vehicle maneuvering back onto the road safely (as cited in Mazzae et al., 2003).

2.2.1.8 Task 7.1: Examination of ABS-Related Driver Behavioral Adaptation – License Plate Study (November, 2001)

Another area of interest that the NHTSA Light Vehicle ABS research program investigated was the possibility of an ABS-related behavioral adaptation. It was hypothesized that drivers with vehicles equipped with ABS may drive faster than those with conventional brakes. The goal of Task 7.1 was to determine if drivers with ABS-equipped vehicles drive faster than other drivers with conventional brakes (Mazzae, Garrott, Barickman, Ranney, & Snyder, 2001).

To measure driver's typical average speed, an unobtrusive measurement method was required. The research team used overpasses to set up a laser speed gun and video camera system. The laser speed gun captured the vehicle's speed, while the video camera recorded the corresponding license plate. The license plate numbers were used to obtain the Vehicle Identification Number (VIN), which allowed researchers to determine if the vehicle was equipped with ABS or conventional brakes. Once the braking system was identified, the speeds were compared between the ABS-equipped vehicles and those with conventional brakes. The data were collected from four different divided highways with two lanes traveling in each direction with a speed limit of 65mph. The pavement was monitored for being either dry or wet, but no formal measurements were made nor was any data collected when it was raining due to the degradation in visibility needed to identify license plates. The data were collected during two different time periods, AM (8:00 AM-12:00 PM) and PM (12:30-4:30 PM), due to visibility concerns no data were collected outside of daylight hours. Cars, light trucks and non-commercial vehicles years 1985 to 2000 were included in this study and broke into three groups: 1985-1989, 1990-1994, and 1995-2000 (Mazzae et al., 2001).

The results of the study showed no effects of brake system on vehicle speed. Though there was an overall trend observed at all sites that ABS-equipped vehicles drove an average of 0.4mph faster than vehicles with conventional brakes, it was not a statistically significant difference. There were significant differences observed between dry versus wet pavement, where drivers tended to drive slower on wet roads than dry roads. It was observed that drivers with newer model year vehicles drove at faster speeds than those with older vehicles. There was also an effect of the data collection site on speed. Since there was no effect of brake system on speed observed in this study, there may not be evidence of behavioral adaptations related to ABS-equipped vehicles. The researchers claim that for an adaptation to occur, drivers must be aware of the equipment that is on their vehicle and feel a difference in performance that is attributed to that equipment (Mazzae et al., 2001). The phone survey that was part of Task 2 showed that many drivers did not know what ABS does, how ABS affects performance, when ABS is functioning or if their vehicle was equipped with ABS (Mazzae, Garrott & Snyder, 2001). In addition, the test track study Task 5.2/5.3 showed no differences in brake pedal forces between drivers with ABS-equipped vehicles and drivers with conventional brakes. Many of the drivers in the test track study did not press the brake pedal with enough force to active ABS in the dry pavement condition (Mazzae et al., 2003). The results of Tasks 2 and 5.2/5.3 in combination with Task 7.1 showed no evidence of a behavioral adaptation due to driver's lack of knowledge and inexperience using ABS that would contribute to an adaptation (Mazzae et al., 2001).

Though this study does not suggest evidence for behavioral adaptation, the study only examined one adaptation. It may be possible that drivers have other adaptations like headway or lane change behavior. The other possibility researchers claimed was that the adaptation behavior was not common with average drivers. For example, the behavioral adaptation could be associated with drivers that take more risks than the average driver or a driver under the influence of alcohol or other substances (Mazzae et al., 2001).

2.2.1.9 Task 7.2: Examination of ABS-Related Driver Behavioral Adaptation – On-Road MicroDAS Study (December, 2002)

Like Task 7.1, Task 7.2 aimed to investigate the possibility of an ABS-related driver behavioral adaptation that results in drivers of ABS-equipped vehicles driving at higher speeds. The goals of this study were to gain naturalistic data from drivers of different ages to investigate behavioral effects related to ABS. Twelve individuals participated in this study, including six males and six females between the ages of 18-25 years (younger) or 40-60 years (older). Participants had to have a minimum of a 45-minute commute one direction with the majority of the route being on the highway with a speed limit of at least 55mph. The study took place over two months, where participants drove test vehicles with ABS enabled and disabled. The test vehicles were all 1996 Chrysler Concordes with ABS, but with cruise control disabled because speed was a variable of interest. The test vehicles were instrumented with a MicroDAS to record vehicle motion data, video cameras to see the environment and driver reaction, as well as a Lecia headway sensor to track the distance between the participant's vehicle and other vehicles. The participants drove the test vehicle for one month with ABS enabled and one month with it disabled. In order to either enable or disable ABS, the participants were told that there were issues with the data acquisition system, and they would be given a similar vehicle for the second month. Participants were given a list of features along with the vehicle, which included if the vehicle had ABS or not, but drivers were told that ABS was an optional feature for the test vehicle. The goal was not to draw attention to the change in the braking system. After the two months of driving, participants completed a questionnaire to gain background information and observations from the study (Mazzae, Garrott, Baldwin, & Snyder, 2002).

In order to compare driving data between participants, the data were broken into segments. The first segment consisted of about four miles of highway driving, while the second segment consisted of about 2 miles of highway driving. The goal was to cut out any large changes in speed associated with stopping or traffic with locations where the speed was not 55mph or higher. Speed, acceleration, lateral control, ABS activations, headway times, lane change behavior, passing behavior and crashes were evaluated for each driver for both brake systems and for both age groups (younger and older, [Mazzae et al., 2002]).

The results showed that there were no significant differences when ABS was enabled or disabled. There were multiple differences between the two age groups, which were analyzed for a validation of the method used. The results showed that younger drivers generally drove faster, made more aggressive lane changes, had shorter headway times and were passed by fewer vehicles when compared to older drivers. There was a total of 17 ABS activations, but only one was caused by a crash avoidance maneuver and all others were caused by braking on irregular road surfaces. The results of this study suggest no ABS-related behavioral adaptation. ABS is rarely engaged, as shown in this study, which suggests that drivers aren't often in panic braking situations, nor do they press the brake pedal with enough force to activate ABS. Since most drivers do not press the brake pedal hard enough, it is unlikely that ABS could help to prevent a crash (Mazzae et al., 2002).

2.2.1.10 Task 8: Assess the Overall Effect of Passenger Car ABS on Drivers' Ability to Avoid Crashes

Task 8 was intended to explore the results of all previous tasks and integrate the findings to assess why there were increases in fatal single-vehicle run-off-the-road crashes. NHTSA was not able to find either hardware deficiencies or driver behaviors that would contribute to the increase in crashes (as cited in Mazzae et al., 2002). Due to the lack of contributing factors, Task 8's report was never published.

2.2.1.11 Task 9: Status Briefings

Task 9 aimed to share the knowledge gained through NHTSA's Light Vehicle ABS Research Program tasks with other organizations, industry and the public, which was also never published (as cited in Mazzae et al., 2002).

2.2.1.12 Summary of NHTSA's Light Vehicle ABS Research Program

NHTSA created the Light Vehicle ABS Research Program to investigate the zero net benefit of crashes surrounding ABS. Though there were some reductions, ABS-equipped vehicles showed increased rates of fatal single-vehicle run-off-road crashes. Multiple hypotheses as to why there were increases in fatal single-vehicle crashes were proposed. The initial analyses of ABS in the early to mid-1990s revealed the issues with single-vehicle crashes, but the vehicles included in these studies were often luxury or sporty vehicles, not representative of typical vehicles (Kahane, 1993; Kahane, 1994 Dec.; Hertz et al., 1995a; Hertz et al., 1995b; Farmer et al., 1996). It was hypothesized that the increase in crashes could be a fluke associated with luxury or sporty vehicles (Garrott & Mazzae, 1999). Task 1 updated the crash data to include vehicles from 1995 and 1996 due to more economy vehicles being equipped with ABS and newer ABS systems, but the same trend of increases in single-vehicle fatal crashes persisted (Hertz, 2000). Another hypothesis was that ABS may not perform as well as conventional brake systems during different maneuvers or on different surfaces, which could cause the increase in single-vehicle crashes (Garrott & Mazzae, 1999). Task 4 aimed to investigate ABS's performance during various maneuvers over multiple surfaces not previously investigated. The results showed that ABS was associated with shorter stopping distances and more vehicle stability compared to conventional brakes on most surfaces and maneuvers. The only exception was gravel, where ABS-equipped vehicles took an average of 27% longer distance to stop compared to vehicles with conventional brakes (Forkenbrock, Flick, & Garrott, 1999).

Once performance of ABS hardware and software was eliminated, the focus shifted to the driver's interaction with ABS. Before ABS, if a driver pressed the brake in a panic situation, the brakes would often lock. Locked wheels skid across the road surface and the driver has no steering control regardless of the steering input the driver gives the vehicle. Since ABS prevents the wheels from locking, drivers remain in control of the vehicle's steering, unlike with conventional brakes. It was hypothesized that retaining steering control resulted in large steering inputs when activating ABS that could cause drivers to run off the road (Garrott & Mazzae, 1999). Task 5.2/5.3 explored crash avoidance behaviors where almost all participants used a combination of braking and steering in attempt to avoid a crash-imminent situation. Though participants did make aggressive and large steering inputs, very few participants had road departures, reducing the likelihood that drivers' steering inputs were the cause of the increase in the number of vehicles running off the road (Mazzae et al., 2003). It was also hypothesized that drivers of ABS-equipped vehicles may have behavioral adaptations like driving faster due to the increase in braking performance of ABS over conventional brakes (Garrott & Mazzae, 1999). Task 7.1 explored a large sample of highway travel to determine if drivers with ABS-equipped vehicles drove faster, but the results did not show any significant findings in speed driven between drivers with and without ABS (Mazzae et al., 2001). This was also the case for Task 7.2 that focused on a smaller group of drivers but monitored their driving behavior over a two-month period. The results showed no differences in speed driven or lane change behavior when driving with and without ABS. In order for driver's to behaviorally adapt, they must have knowledge of the performance benefits and feel them (Mazzae et al., 2002). Interestingly, the results of Task 2 showed that many drivers did not have knowledge of how ABS effects performance or experience activating ABS (Mazzae, Garrott & Snyder, 2001). Therefore, it is unlikely there were ABS-related behavioral changes. Though Task 2's results showed lack of knowledge and experience with ABS, there was no evidence of dangerous reactions like releasing the brake pedal in response to the noise and vibration feedback when ABS activates (Kahane & Dang, 2009).

The results of NHTSA's Light Vehicle ABS Research Program did not find significant issues with ABS. The majority of drivers did not have knowledge and experience with the system, thus there was little evidence of ABS-related behavioral adaptations that could be responsible for the increase in run-off-road crashes (Kahane & Dang, 2009).

Though NHTSA explored driver behavior and found no significant differences between those driving vehicles with ABS and conventional brakes, the lack of knowledge and experience with ABS showed no changes in braking force between ABS and conventional brakes. Only 32% of participants in Task 5.2 on dry pavement activated ABS during the incursion scenario, therefore only a third of participants utilized their brake effectively (Mazzae et al., 2003). Though the results of the tasks collectively show drivers lack knowledge and ability to effectively activate ABS in a crash-imminent situation, NHTSA did not investigate if practice or training to activate ABS made differences in crash avoidance behavior or produced behavioral adaptations. In Task 5, drivers crash avoidance behavior was studied using either a high-fidelity simulator using a full vehicle (Task 5.1 [McGehee et al., 2000]) or vehicles on a test track (Task 5.2/5.3 [Mazzae et al., 2003]). A portion of the participants in the ABS condition were shown an instructional video on ABS operation created for use during the vehicle purchasing process. There were no differences in crash avoidance behavior between the participants that had watched the instructional video before the test scenario versus those who had not (McGehee et al., 2000; Mazzae et al., 2003). Task 5.2 also included a braking practice, where participants in both the ABS and conventional brake groups had three practice trials to avoid a cone in the center of the lane (similar to incursion event) without any input from the researchers on braking technique. Like the ABS video instruction, the braking practice made little difference in crash avoidance behavior and had no effect on the number of participants that activated ABS (Mazzae et al., 2003). The results of the NHTSA Light Vehicle ABS Research Program show that knowing the vehicle is equipped with ABS, watching an instructional video on ABS and practicing braking without any instruction to use ABS or feedback on their performance activating ABS, did not make any difference in drivers' performance. Therefore, practice and training using ABS should be investigated further. The NHTSA Light Vehicle ABS Research Program was solely focused on adult drivers, the knowledge and driving behaviors of novice teen drivers were not included.

2.2.2 Long-term evaluation of ABS (2009)

Though ABS was not made required equipment on vehicles in the US at the conclusion of NHTSA's Light Vehicle ABS Program, as part of the NHTSA's 2008-2012 evaluation plan ABS was evaluated because it was common equipment on vehicles and long-term effects of the system were unknown. The study included crash data from 1995 to 2007 from FARS and the General Estimates System (GES [Kahane & Dang, 2009]).

The results showed significant reductions for ABS-equipped vehicles involved in nonfatal crashes, but no net effects for fatal crashes (see Table 3). Nonfatal crashes for passenger cars with ABS decreased by 6% for all crash involvements on all roads, where large decreases in the multi-vehicle crashes overshadowed the increased rates of side impacts with fixed objects. Similarly, LTVs showed an overall 8% decrease in all crashes on all roads with decreases in the majority of crash scenarios with the exception of crashes with pedestrians, bicyclists and animals. Unlike nonfatal crashes, fatal crashes for vehicles equipped with ABS showed more increases in crashes, especially those related to run-off-road crashes, which were especially high in wet, snowy, or icy conditions (Kahane & Dang, 2009).

Table 3. Comparison in crash data between all crashes and fatal crashes for passenger cars and LTVs with ABS on all roads and exclusively wet, snowy, or icy roads (Kahane & Dang, 2009). Negative values show decreases, while positive values show increases in crash rates.

All crashes	All roads		Wet, snowy, or icy roads	
Crash type	Cars	LTVs	Cars	LTVs

All crash involvements	-6%*	-8%*	-16%*	-14%*
Multi-vehicle	-17%	-20%	-37%*	-36%
Pedestrian/bicyclist/animals	8%	42%*	8%	10%
Run-off-road	1%	-11%	13%	-3%
• Side impacts with fixed objects	20%*	9%	43%*	15%
• First-event rollovers	-3%	-17%	12%	-6%
• All other	-5%	-15%	3%	-9%
Fatal crashes	All roads		Wet, snowy, or icy roads	
Crash type	Cars	LTVs	Cars	LTVs
All fatal involvements	-1%	1%	1%	6%
Multi-vehicle	-4%	1%	-12%*	6%
Pedestrian/bicyclist/animals	-13%*	-14%*	-	14%
Run-off-road	9%*	6%	34%*	10%
• Side impacts with fixed objects	30%*	-	85%*	4%
• First-event rollovers	11%	10%	52%*	31%*
• All other	3%	5%	17%*	3%

* Statistically significant

Though the percentages of fatal run-off-road crashes for vehicles with ABS are lower than in previous studies like Kahane (1994) and Farmer et al. (1996), there is still a statistically significant negative effect on run-off-road crashes. These results suggest that there are not large differences between older vehicles or ABS systems in comparison to newer vehicles and ABS systems. The authors of this study suggest the negative effects of run-off-road crashes from the evaluations of vehicles with ABS prior to 1995, could be related to drivers' lack of knowledge and use of ABS. In 1995, NHTSA, automotive manufacturers, ABS suppliers and the insurance industry worked together to create ABS relevant media for the public. The media gave an overview of proper operation, expected feedback when ABS is activated, steering control, performance on various road surfaces, and driving behaviors. Since releasing this ABS-related media, it may be possible that more drivers had increased knowledge and experience with ABS, which could have been the reason for a decrease in the overall percentage of run-off-road crashes between the 2009 evaluation and those conducted prior to 1995. Since there was still a negative effect of ABS-equipped vehicles on run-off-road crashes, the authors suggest that it could be due to a portion of drivers that are still lacking knowledge of ABS or lack of experience because ABS activation is infrequent (Kahane & Dang, 2009).

2.3 ABS and Electronic Stability Control (ESC)

Though ABS helps drivers to retain steering control during heavy braking, ABS is not able to help drivers with uncontrollable vehicle rotation (yawing) due to steering input that can cause loss of traction. Electronic Stability Control (ESC) was developed to help prevent loss of traction by automatically making braking adjustments at the individual wheels and/or reducing engine output. ESC compares the driver's intended course, which is extracted from the steering wheel angle, with the actual movement of the vehicle based on the speed of each wheel, yaw rate and lateral acceleration of the vehicle. If the driver's intension does not match the vehicle's motion, ESC makes corrections (Dang, 2007). Unlike ABS, ESC is automated and does not require the driver to activate the system and can prevent a crash before the driver is aware of the situation. ESC utilizes the same technology as ABS, like monitoring the wheel speed and modulating brake pressure at each wheel. ABS capabilities are only a subset of those of ESC, but because the same functionality is used, ABS is typically equipped in vehicles with ESC (Kahane & Dang, 2009).

ESC began appearing on luxury vehicles in 1997 and by 2004 enough vehicles had been equipped with ESC to evaluate changes in crash occurrences. Unlike ABS, ESC showed overwhelming positive effects on the initial evaluation. Single-vehicle crashes were reduced by 35% in passenger cars and 67% in LTVs. For fatal single-vehicle crashes, 30% reductions were observed in passenger cars and 63% in LTVs (Dang, 2004). As a result of the initial analysis of ESC, the Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users of 2005, Section 1031 requested an official ANPRM on stability-enhancing technologies to NHTSA in April of 2006 (Federal Register Notice 71: 54712; Kahane & Dang, 2009). NHTSA published the official ANPRM in September of 2006, which was finalized in April of 2007 (Federal Register Notice 72: 17310), establishing FMVSS No. 126 requiring ESC on all new passenger cars and LTVs by September 2011 (NHTSA, 2007). NHTSA required automotive manufactures to use a phased-in approach to adding ESC to their vehicle fleet beginning in September 2008. Though FMVSS No. 126 does not explicitly require ABS, automotive manufactures include ABS on vehicles with ESC (Kahane & Dang, 2009). Modern ESC systems combine ABS and ESC in a single unit (Continental AG, 2019).

In 2007, Dang published an updated evaluation of ESC that included vehicle model years from 1997 to 2004. The results showed the same reductions in crashes like the initial evaluation (Dang, 2004), where single-vehicle crashes were reduced by 26% in passenger cars and by 48% in LTVs. Fatal single-vehicle crashes for passenger cars were reduced by 36% and 63% for LTVs (Dang, 2007). Within the 2009 long-term evaluation of ABS by Kahane and Dang, crash reductions for vehicles with ABS and ESC were estimated and compared to vehicles with only ABS. Kahane and Dang (2009) utilized the data from Dang's 2007 evaluation of ESC. When combining the effects of ESC and ABS, the results show increases in crash reductions for nonfatal (14% for passenger cars and 17% for LTVs) and fatal crash involvements (15% for passenger cars and 27% for LTVs; see Table 4). ABS offers benefits primarily in reducing the number of multi-vehicle crashes, where ESC counters the negative effects of ABS on single-vehicle fatal run-off-road crashes (Kahane & Dang, 2009).

Table 4. Comparison of crash involvements for vehicles with ABS, ESC and both ABS and ESC (Kahane & Dang, 2009)

All crashes	Passenger cars			LTVs		
Crash type	ABS	ESC	ABS & ESC	ABS	ESC	ABS & ESC
All crash involvements	-6%	-8%	-14%	-8%	-10%	-17%
Run-off-road	1%	-45%	-44%	-11%	-72%	-75%
Multi-vehicle	-17%	-13%	-28%	-20%	-16%	-33%
Fatal crashes	Passenger cars			LTVs		
Crash type	ABS	ESC	ABS & ESC	ABS	ESC	ABS & ESC
All fatal involvements	-1%	-14%	-15%	1%	-28%	-27%
Run-off-road	9%	-36%	-30%	6%	-70%	-68%
Multi-vehicle	-4%	-19%	-22%	1%	-34%	-33%

2.2 Current Crash Statistics

Even with ABS, there are still a disproportionately high number of rear-end crashes in the US, where a vehicle crashes into the rear or back of another vehicle. There were over two million rear-end crashes in 2015, which accounts for 33.4% of all crashes, 6.8% of fatal crashes, 32.4% of all injury causing crashes, and 33.9% of crashes resulting in property damage only (NHTSA, 2017b). For fatal crashes in the US, 39% involved collisions with another vehicle and 7.2% were rear-end crashes in 2017 (NHTSA, 2019b).

2.3 Literature Overview

Though the primary focus of the dissertation is on ABS, Chapters Three through Five of this document have a broader focus. Chapters Three through Five explore teens', parents', and adults' views of different post-license advanced driving programs. Both programs consisted of multiple exercises that participants experienced while driving on a closed-road course, which included an ABS exercise. During the ABS exercise, participants actively tried to activate ABS. Chapters Three through Five were necessary studies leading to the sole focus on ABS.

Each chapter's background information section varies based on the study and driver age group. Chapter Three gains the views of teenage drivers participating in a post-license advanced driving program. The background research included in Section 3.1 of Chapter Three presents teen crash statistics, licensure requirements in the US, driver's education in the US, an introduction to post-license advanced driving programs for teens and the half-day Guard Your Life Challenge Program. The information contained in Chapter Three is focused on teen drivers and their background knowledge based on driver's education and the licensure process. Chapter Four expands upon Chapter Three by gaining the views of parents in addition to the teens of a post-license advanced driving program. The background research in Section 4.1 is focused on parents' role in their teen's driving experience as well as an overview of the half-day Guard Your Life Challenge program. Chapter Five gains the views of both teen and adult drivers participating in a one-day car control course. The background information included in Section 5.1 covers both US and international driver's education, licensure requirements and crash statistics. Section 5.1 gives an overview of US teen and adult post-license advanced driving programs as well as the car control class.

CHAPTER THREE: STUDY I - TEENAGE DRIVERS' VIEWS OF A CLASSROOM AND CLOSED-ROAD POST-LICENSE DRIVING PROGRAM, GUARD YOUR LIFE

The results of this study were published in Safety in September 2020 with the following citation: Mims, L., Brooks, J. O., Jenkins, C., Schwambach, B., & Gubitosa, D. (2020b). Teenage Drivers' Views of a Classroom and Closed-Road Post-License Advanced Driving Program, Guard Your Life. *Safety*, 6(4), 44.

3.1 Introduction

In the US, teenage drivers are at a greater risk of being involved in a crash than any other age group. There are multiple industries working to improve teenage drivers' safety, especially through education and vehicle technologies. Post-license advanced driver training programs have emerged with the goal of teaching the skills needed to prevent and mitigate an emergency situation. The Guard Your Life Challenge program is a post-license advanced driving program focused on educating teenagers about proper use of the anti-lock braking system (ABS), the correction needed to recover from a skid, and the dangers of distraction.

3.1.1 Teen Crash Statistics

Teenage drivers only account for approximately 5% of licensed drivers in the US (National Highway Traffic Safety Administration [NHTSA], 2018b) but make up a disproportionate number of fatal crashes. In the US, the leading cause of death for teenagers is motor vehicle crashes (Center for Disease Control and Prevention's National Centers for Injury Prevention and Control [CDC], 2017). Driver error is the most common cause for teenagers to be involved in crashes. The most common types of errors by teenagers include recognition errors (visual scanning errors, distraction), decision errors (following distance, vehicle speed relative to conditions), and performance errors (losing control) (Curry, Hafetz, Kallan, Winston, and Durbin, 2011). Teenage distractions are commonly related to cognitive distractions (e.g., inattentive, lost in thought, and looked but did not see) and in-vehicle technology-related distractions (e.g., cellphone use, audio and climate controls) in comparison to other age groups (Qin, Li, Chen, Bill and Novce, 2019). In addition, it is also documented that roadway-related factors (e.g., lane width, medians, and road curvature) as well as weather factors (e.g., visibility and road surface conditions) affect a driver's driving behaviors (Hamdar, Qin, Talebpour and Weather, 2016). For teenagers, the most common single-vehicle crashes involve vehicles running off the road, both on straight roads and negotiating curves. The most common multiple vehicle crashes for teenagers include rear-end collisions and turning into the path of an oncoming vehicle in intersections (McDonald, Curry, Kandadai, Sommers and Winston, 2014).

Due to the number of crashes associated with teenage drivers, multiple industries have been working to address this problem. The government, at both the national and state levels, has updated laws and implemented a licensure process to promote the importance of teenage driver safety. Automotive companies and researchers have focused their efforts to make vehicles safer through engineering systems that help the driver avoid and mitigate dangerous situations.

3.1.2 License Requirements

In the US, a graduated driver's license is typically required for a young individual to drive independently. With a graduated driver's license, there are various phases to help the driver gain experience before transitioning to an unrestricted license. The first phase is obtaining a learner's permit, allowing an individual to practice driving with a licensed adult. Typically, the permit can be obtained at age 15 and older, after passing a written knowledge test of the laws and policies, as well as a vision screening (NHTSA, 2017a). Most states require the individual to hold a permit for at least a six-month period but can be up to 12 months depending on the state, before taking the on-road driving test to earn a license (Fisher, Caird, Horrey and Trick, 2016).

In order to gain a license and drive independently, a driver must pass their state's on-road driving test. If the driver is under the age of 18, the individual may have to complete a driver's education course before taking the on-road driving test (NHTSA, 2017a), or in states that do not require driver's education, the driver takes the on-road driving test when they feel that they are ready (Fisher et al., 2016). In some states, the driver is required to show documented supervised practice driving time outside of driver's education, which can vary, but on average consists of 50 h; some states also include 10 h of nighttime driving (Fisher et al., 2016). The on-road driving test varies by state but generally consists of being able to drive with regular street traffic, while maintaining appropriate speed and lane position. The test also includes basic vehicle maneuvers such as left and right turns, backing up and parking (e.g., Florida Department of Highway Safety and Motor Vehicles, 2018; Georgia Department of Driver Services, 2018; State of California Department of Motor Vehicles, 2017; Texas Department of Public Safety, 2017).

Once the on-road test is passed, if the driver is older than the age of 16, but younger than 18, a restricted license is granted. Restrictions vary by state but commonly restrict the number of passengers and/or a curfew (Fisher et al., 2016). Once the driver turns 18, the restrictions are removed. If the driver is over the age of 18 when the license exam is passed, there may be no restrictions, and they will have all the privileges of a full license.

3.1.3 Driver's Education

Today's typical driver's education requirements include 30 hours of classroom education, six hours of on-road instruction and six hours of in-vehicle observation (NHTSA, 2017a). On-road instruction refers to the teenager driving the vehicle, and observation refers to watching other teenage drivers receiving feedback from the instructor during their on-road instruction (NHTSA, 2017a). While driver's education courses aim to teach teenagers how to become safe on the road, the course mainly takes place in the classroom, and therefore the students' driving skills may not develop further than the basics (Fisher et al., 2016).

Many studies have been conducted to evaluate the effectiveness of driver's education in the US. Williams and Ferguson (2004) found that there were no differences in the crash records of drivers who had taken a driver's education course and those who learned to drive without taking the course. A review of the literature conducted by Peck (2011) found that there was no conclusive evidence showing that driver's education reduces teenagers' crash rates. These studies suggest that driver's education in the US is tailored towards equipping young drivers with the necessary skills to operate a vehicle under normal driving conditions but may not teach skills needed to avoid or mitigate crashes.

Though there is speculation surrounding the effectiveness of driver's education, many still feel it is important in preparing young drivers. A survey conducted in the US showed that 86% of people considered driver's education courses to be "very important" in the training of new drivers (Williams and Ferguson, 2004) and many believe that they are instrumental in producing safe drivers (Fisher et al., 2016). Interestingly, another survey study found that approximately half of teenagers and parents did not feel that driver's education completely prepared teenagers for driving (Michelin, 2014).

3.1.4 Vehicle Technology

In order to help reduce the number of vehicle crashes, the automotive industry has developed multiple vehicle technologies to address some of the most common critical crash scenarios. In 2015, the National Highway Traffic Safety Administration (NHTSA) reported that for all drivers, 70% of all crashes were with another vehicle and 33% of all crashes were rear-end collisions with other vehicles (NHTSA, 2017b).

Anti-lock braking systems (ABS) were developed to address single-vehicle crashes caused by skidding or loss of control during panic braking. The system operates by optimizing the brake pressure to prevent skidding caused by wheel lockup, which allows the driver to control and steer the vehicle (Kahane, 1994). The system quickly holds and releases the brake pressure, resulting in vibration feedback in the brake pedal when engaged. Though ABS has been incorporated into vehicles since the 1980s, ABS was not required until years later due to an increase in crashes involving vehicles running off the road (Kahane, 1994). In 1998, the NHTSA evaluated ABS to find that drivers did not understand the feedback from the pedal when ABS was engaged, which could have caused dangerous driver reactions such as releasing the brake pedal (Mazzae, Garrott, & Snyder, 2001). In 2012, ABS became required equipment for all new vehicles (NHTSA, 2007) as part of the Electronic Stability Control (ESC) system. In the US, drivers are not mandated to activate ABS during the graduated driver's licensure test (e.g., Florida Department of Highway Safety and Motor Vehicles, 2018; Georgia Department of Driver Services, 2018; State of California Department of Motor Vehicles, 2017; Texas Department of Public Safety, 2017). Drivers in some states may be asked to stop quickly, but there is no activation of ABS requirement (e.g., Florida Department of Highway Safety and Motor Vehicles, 2018; Texas Department of Public Safety, 2017).

Electronic Stability Control (ESC) systems were developed to reduce yawning or rotation caused by steering input that results in loss of traction that ABS cannot eliminate. ESC makes braking adjustments at the individual wheels and/or reduces the engine output by comparing information from the vehicle's movement (individual wheel speed, yaw rate and lateral acceleration) with the inputs from the driver (steering wheel angle) (Dang, 2004). ESC has shown to be effective in reducing the number of crashes for drivers of all ages, especially single-vehicle crashes (Sivinski, 2011). ESC relies on the available traction and cannot create more. If the road surface is slippery (low coefficient of friction), the ESC system may not be able to overcome the lack of tire grip to prevent loss of traction (Papelis, 2006). Situations such as emergency maneuvers to avoid another vehicle, sudden changes in environmental conditions, and road departures, especially on curves, can result in large losses of traction that can cause the car to skid unintentionally (Ferguson, 2007). Knowing the appropriate actions to take to restore traction for both understeer (front wheel skid) and oversteer (rear wheel skid) are not skills required to pass the driving test (e.g., Florida Department of Highway Safety and Motor Vehicles, 2018; Georgia Department of Driver Services, 2018; State of California Department of Motor Vehicles, 2017; Texas Department of Public Safety, 2017).

3.1.5 Post-License Driving Programs

Acknowledging that the licensing process, driver's education, and new vehicle technologies may not provide young drivers all of the skills or assistance needed to mitigate emergency situations, multiple post-license driving programs have emerged in the US. Different organizations ranging from non-profits (e.g., https://putonthebrakes.org, https://teendrivingsolutions.org/course), foundations (e.g., http://www.southmetrofoundation.org/136/Teen-Crash-Avoidance-Skills), private driving companies (e.g., https://www.drivesafer.com/courses/drive-safer-basic-car-control-and-defensive-driving-course, http://www.birperformance.com/streetsmarts) , police/sheriff's departments (e.g., https://www.flsheriffs.org/law-enforcement-programs/our-programs/teen-driver-challenge), automotive manufacturers (e.g, https://www.drivingskillsforlife.com), etc., are offering driving programs. Skills taught at each of these programs vary based on location/facilities, instructors, and cost, but the goals commonly focus on how to use the vehicle's safety systems and the importance of understanding the impact of driver distraction. These programs emphasize behind-the-wheel experience, allowing the driver to make errors, receive feedback, and make the appropriate corrections, which is an essential learning process for retaining information in long-term memory (De Groot, Ricote and Winter, 2012).

Though many programs are believed to be effective in reducing the number of teenagers involved in crashes, there is limited data showing what teenagers believe they gain through a post-license driving program.

3.1.6 Guard Your Life Challenge Program

The Humphries family lost their teenage daughter, Victoria, in a single-vehicle crash in July 2012 after she lost control of her vehicle at night and ran off the road. The crash environment was all too similar to many single-vehicle teenager fatalities. This tragedy led the family to create a non-profit, post-license driving program, the Guard Your Life (GYL) Challenge program (http://www.guardyourlifechallenge.com). The half-day program is offered four times a year, with a maximum of 30 teenagers per session. Two sessions are offered each day, with a morning and afternoon session.

The program starts in a classroom setting prior to driving through the exercises on the closed-road track. Parents are encouraged to stay for the classroom portion and the majority of parents stay to watch the driving component. Each program starts with a video that includes the TV news clip that aired immediately after Victoria's crash along with interviews filmed a couple of years later with law enforcement officers and Victoria's family members (see https://www.youtube.com/watch?v=WeGbD9-hchU). Then, a spokesman from the state's Highway Patrol speaks about teenager crash and fatality statistics on a local and national level. The officer explains the physics of what happens to one's brain and body during a crash using Newton's laws of inertia and force in easily understood terms. Finally, the officer discusses distracted driving ("Policy Statement and Compiled FAQ…", n.d.), explaining the visual, physical, and cognitive components using examples that are applicable to both the teenagers and their parents.

Next, the performance center's driving instructors provide short introductions, including a description of how many years of experience and what professional racing licenses each instructor has. Then, the lead instructor provides classroom instruction on diverse concepts including the importance of knowing where to look, proper hand and seating position for driving, and mirror adjustment for minimizing blind spots. The instructors also give an introduction to ABS, oversteer, understeer, and how to anticipate and make corrections in a loss of traction situation. Then, the instructor provides an overview of the track (see Figure 10) and the three practice exercises: emergency braking, skid recovery and the distraction exercise (see Figure 11).

Figure 10. Aerial view of the track with the locations of the 1 ABS braking, 2 skid recovery, and 3 distraction exercises indicated.

(**a**) (**b**) (**c**)

Figure 11. (a) A driver learning how to recover from a skid, (b) a driver activating the ABS brakes, and (c) a driver completing the distraction exercise with an instructor on the track providing feedback

The teenage drivers are divided into three groups of ten for the track exercises and have a short break when rotating between each of the three exercises. The teenagers use new (2016 model year and newer), identical vehicles on each track exercise during the GYL program.

The teenage drivers practice understeer and oversteer skid recovery on a wet track. Understeer is where a driver has lost grip with the front tires and the vehicle will not respond to steering inputs (often happens when a driver is going too fast into a corner). In understeer situations, drivers are instructed to be patient, lift their foot from the accelerator, not add more steering and keep one’s eyes on the intended path while waiting for the front tires to regain traction. In an oversteer situation, the driver has lost grip with the rear tires and the back of the car wants to essentially pass the front. To correct an oversteer situation, the “CPR” method is taught: correct, pause (wait to regain traction or grip), then steer to recover (see Figure 11a). At the beginning of this exercise, ESC is left on for a few laps for the teenage drivers to feel the system working to keep traction. Then, ESC is turned off to allow the teenage drivers to experience a skid while training the corrective actions. The instructors let the teenagers make errors, then give feedback to help them understand the difference in feeling and corrective action needed to be executed.

The emergency braking exercise allows teenagers to experience ABS in a controlled environment (see Figure 11b). The teenage drivers are instructed to stay relaxed, keep one’s eyes up, looking where they want to go (rather than looking down inside the vehicle), stomp on the brake pedal, keep the brakes fully depressed until the vehicle comes to a complete stop and steer when necessary. This exercise begins with the vehicles going 30–35 miles per hour and continuously increases up to 55 miles per hour during each trial, so the teenagers gain an understanding of how braking distance changes with speed. The teenagers receive feedback on their performance after each trial.

The distraction exercise provides first-hand examples of visual, manual and cognitive distractions by requiring the teenagers to drive through a cone course while using their phone to text. During the distraction exercise, one instructor is in the vehicle with the teenage driver while additional instructors cause distractions outside of the vehicle (see Figure 11c).

All teenagers and parents return to the classroom after the driving portion. The instructors give a summary of the primary concepts introduced and emphasize that if one is in an imminent crash situation, it is best to stomp on the brake to slow down the vehicle as much as possible.

While the GYL program and performance driving center have received anecdotal feedback on the effectiveness of the program, no formal evaluation was previously completed. The purpose of this study was to gain the teenagers' views of the Guard Your Life Challenge program by surveying participants immediately after the program and then conducting a phone interview three months later.

3.2 Methods

3.2.1 Participants

To be part of the Guard Your Life (GYL) Challenge program, teenagers must be between 15 and 19 years old and have a restricted or regular driver's license. During the one-year study timeframe, eight half-day GYL sessions were offered and a total of 200 teenagers completed the program; see Figure 12. From this group, 134 teenagers completed the survey immediately after the program; participants included 72 males and 62 females, with an average age of 16.42 years (SD = 1.01). Of the 134 participants, 103 volunteered to be contacted for the follow-up phone interview. Fifty participants completed the follow-up phone interview, including 25 males and 25 females who ranged from 15 to 20 years, with an average age of 16.72 years (SD = 1.01).

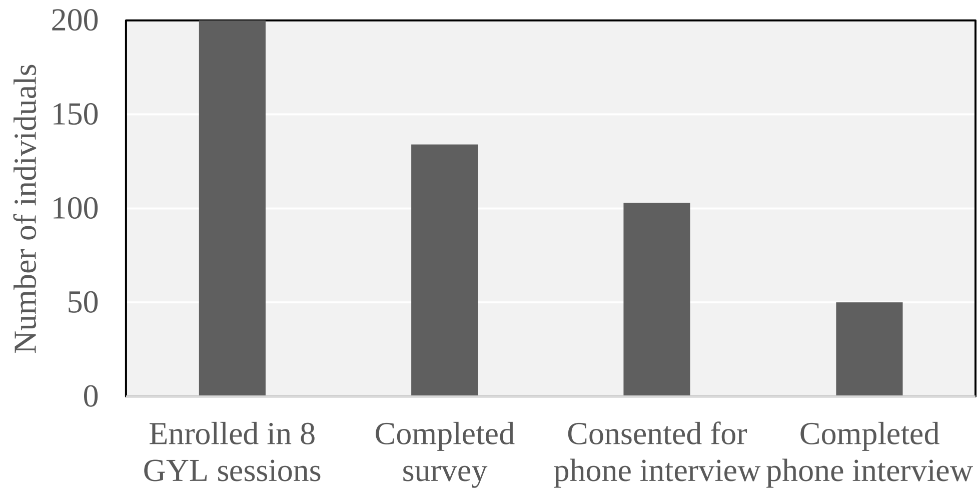


Figure 12. Survey and phone interview participants.

3.2.2 Procedure

All subjects read the consent form and provided their written approval prior to participating in this study. Since many of the participants were teenagers, all participants under the age of 18 years had written permission from a parent. This study was conducted in accordance with the Declaration of Helsinki and the protocol was approved by the Ethics Committee at Clemson University (IRB2015-258).

3.2.2.1 Survey

Immediately after the driving portion of the program, the group returned to the classroom for closing remarks and to complete the survey. It took approximately 10 to 15 min to complete the survey. See Table 5 for an overview of the survey items. With the exception of yes/no questions, all questions were open ended.

Table 5. Survey and follow-up phone interview questions. Words in italics were used for the follow-up phone interview.

Survey	Interview	Questions

X	X	What is your age?
X	X	What is your gender?
X	X	What are the top five things you got out of *(remembered from)* the program?
X	X	Describe the program in 3 words.
X	X	What is the most important or interesting thing you learned?
X	X	Do you think you will use *(have you used)* any of the skills you learned?
	X	*Did using these skills help you to avoid a crash?*
X	X	Do you think you will change *(have you changed)* any of your driving behaviors?
	X	*Rate on a 1-5 scale where 1 is not at all and 5 is extremely, how helpful and informative the program was.*

3.2.2.2 Follow-up phone interview

Each participant was called up to three times, approximately three months after the program. The phone interview consisted of similar questions to the survey and took between 10 and 15 min to complete; see Table 1. With the exception of yes/no questions, all questions were open ended.

3.2.2.3 Data organization

For each open-ended question, all of the participants' responses were combined and sorted by grouping similar responses together, forming categories. These categories turned into topical areas—for example, the topical area of ABS braking contained responses such as brake hard, stomp on the brake and emergency braking. The number of responses for each topical area were tallied to determine the most common responses. There were often more topical areas from each question than what is represented in the most common response figures. To represent all topical areas and actual response language from the participants, word clouds were used. Word clouds are visual representations of large text-based data sets, where importance is represented by size (Siefert et al., (2008). All relevant words or phrases that participants responded with were entered into word clouds to present a visual representation of all topical areas, with the more frequent responses being larger.

3.3. Results

3.3.1 Top Five Things from the Program

On the survey, the participants listed the top five things they got out of the program. All 134 participants responded to this question, resulting in 639 responses. The average number of responses provided was 4.8, ranging from 1 to 5 responses (SD = 0.7). Figure 13a shows the most common responses in a word cloud, with the more frequent responses being larger. During the phone interview, participants named the top five things they remembered from the program. All 50 participants responded to this question, resulting in 219 responses. The average number of responses was 4.38, ranging from 2 to 5 responses (SD = 0.97); see Figure 13b.

(**a**) (**b**)

Figure 13. Word cloud of the top five things from the program: survey (a) and interview (b).

The data categorization revealed that responses fell within six topical areas. The topical areas in order of frequency were braking, distractions, skid/drift, sight and safety. For the braking topic, participants provided answers such as “the ABS system and how it works” as well as “stopping distance”. For the distractions topic, typical answers included “distracted driving is unsafe driving” and “understanding that what you think isn’t a distraction, is”. For the skid/drift topic, responses included “correct, pause, recover” and “how to correct over/under steer”. For the sight topic, responses were “look where you want to go” and “every second of eyes off the road is like a football field”. For the safety topic, responses were “safe habits” and “think before you do”.

The graph comparing the survey and phone interview topical areas shows that three months later, distractions were the most commonly reported topical area followed by braking and skid/drift, followed by sight, safety and facts/stories; see Figure 14. When comparing the similarities of the types of responses between the survey and the phone interview, the participants provided similar examples for both time periods, with the exception of the facts/stories topical area, which were more frequently reported during the phone interview. Examples of facts/stories responses included how frequently teenage driving deaths occur and the story about the fatality that inspired the class.

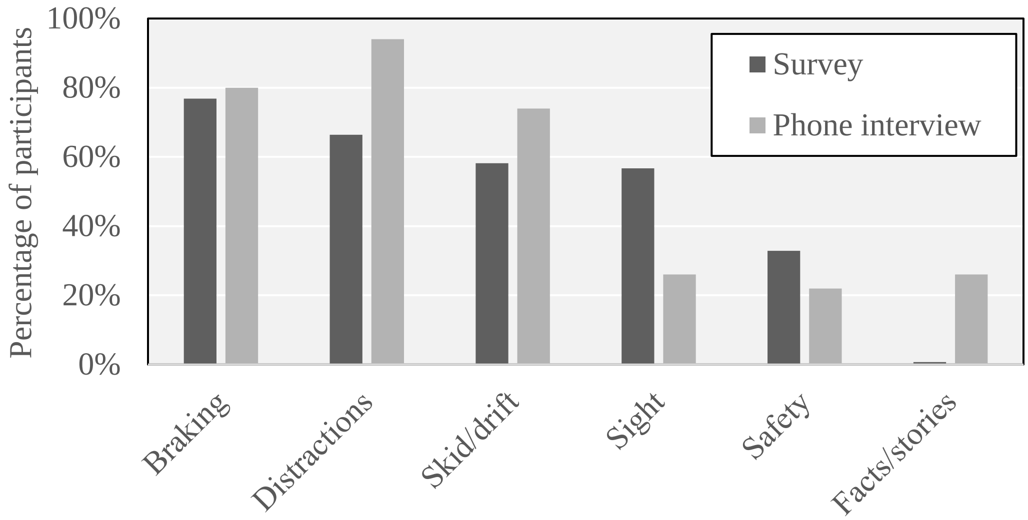


Figure 14. Topical areas for the top five things from the program: survey vs. phone interview.

3.3.2 Key Words

Next, participants described the program in three words. All 134 participants responded to the question, resulting in 394 total responses. The average number of responses per participant was 2.9, ranging from 1 to 3 (SD = 0.3). Figure 15a shows the most common responses in a word cloud. During the phone interview, participants described the program in three words. All 50 participants responded, giving a total of 144 responses, ranging from 1 to 3 responses per participant with an average of 2.9 responses (SD = 0.4); see Figure 15b.

(**a**) (**b**)

Figure 15. Word cloud of key words: survey (a) and interview (b).

The top five key words were very similar between the survey and phone interview. Though the answers overlap, the survey responses reflected the raw emotions the teenagers experienced during the program including fun, exciting, and awesome. The interview responses focused more on the underlying meaning of the program such as informative and helpful. The graphical comparison between the survey and phone interview key words is shown in Figure 16.

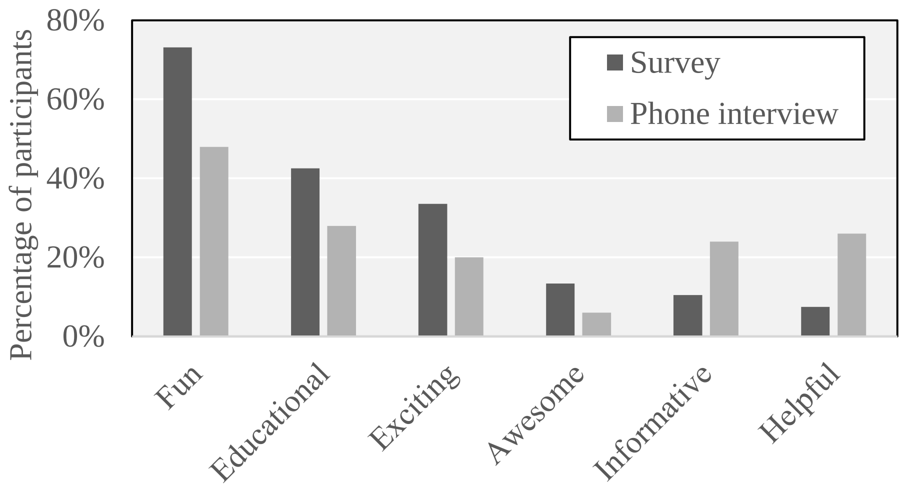


Figure 16. Key words: survey vs. phone interview.

3.3.3 Most Important Thing Learned

On the survey, participants reported the single most important thing they learned during the program. Of the 134 participants, 130 gave a response. Figure 17a shows the most common responses in a word cloud, illustrating that the skid control task was important to the participants. During the phone interview, participants were asked what the single most important thing they learned was and all 50 participants provided responses. The skid recovery skill was the most common response for both the survey and the phone interview (Figure 17b)

(a) (b)

Figure 17. Word cloud of the most important thing learned: survey (a) and interview (b).

The data organization revealed that participants' responses fell within eight topical areas, shown in Figure 18. The most frequent topical areas were skid/drift, sight, and braking. The most frequent topical areas from the phone interview were skid/drift, braking, and distractions. The survey responses were more focused on the technical aspects of driving such as "where to look" and "keeping control of the vehicle." The phone interview responses focused more on the cognitive aspects of driving such as "knowing the dangers of driving" and "knowing how to deal with yourself in high-risk situations."

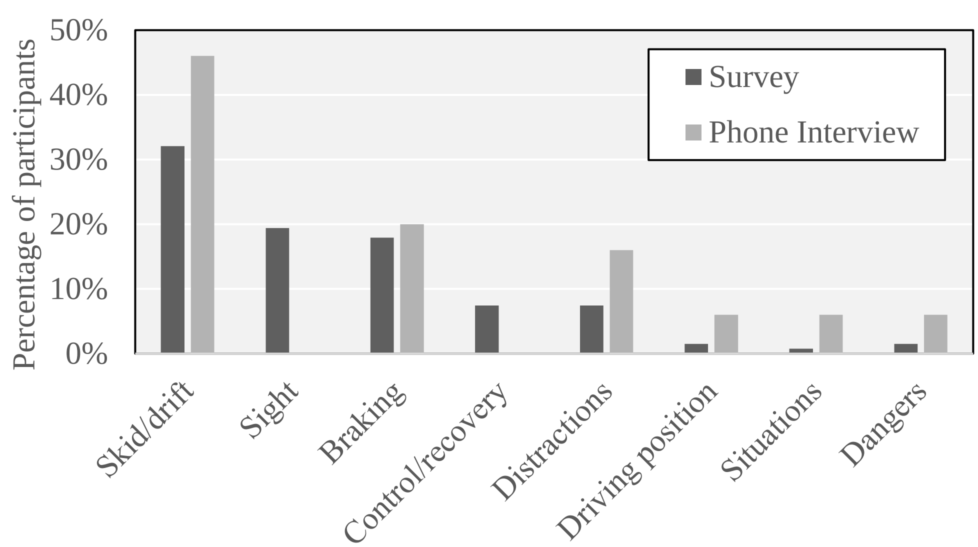


Figure 18. Most important thing learned: survey vs. phone interview.

3.3.4 Use of Skills Learned

The participants were asked on the survey whether they think they will use the skills that they learned in the program. Of the 134 responses, 132 (99%) responded “yes” and 2 (1%) responded “no”. During the phone interview, participants were asked whether they had actually used any of the skills that they learned in the program. All 50 participants responded and 72% had used the skills that they learned in the program on the road in the past three months.

For those who responded with a “yes” on the survey or phone interview, follow-up questions asked for a description regarding what skills that they anticipate they will use (on the survey) or which skills that they actually used (on the phone interview). On the survey, when predicting future skills that they anticipate using, the responses fell into seven topical areas. One topical area was emergency situations, and responses included “being prepared and knowing what to do”. Another topical area was everyday situations, and an example response for this area included “using them anytime on the road.” Skid/drift responses from the survey predicting future use focused on knowing how to drive in the rain and respond appropriately when hydroplaning or sliding. The responses from the phone interview were about skills that they actually used since the program including recovering from a skid. Similar responses occurred with braking, where the survey indicated responses such as not being afraid to brake hard while the phone interview included specific instances of needing to brake suddenly on the road. Distraction responses from the survey focused on not being distracted in the future, while the phone interview responses provide more detailed examples of changes participants made to be less distracted, including ways of preventing others in the car from distracting them such as turning down the music. The topic of safety increased in frequency from the survey to the phone interview, where participants reported being more careful/cautious, and provided a greater distance to the vehicles in front of them. Sight or “looking where you want to go” was also a consistent response on both the survey and the interview. The topical areas for the responses on the survey and phone interview are displayed in Figure 19.

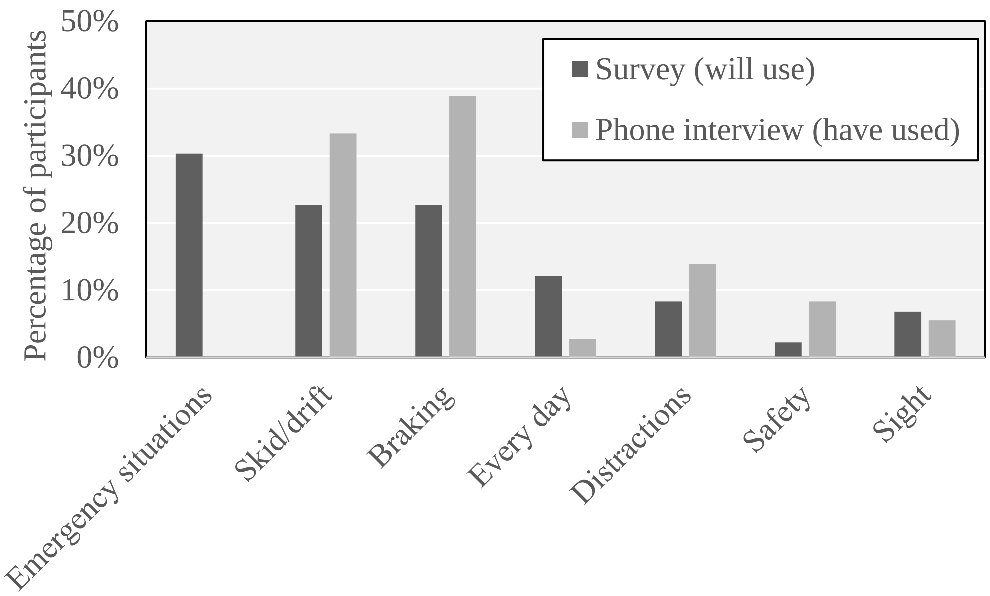


Figure 19. Topical areas for use of skills learned: survey vs. phone interview.

3.3.5 Did Using the Skills Learned Help to Avoid a Crash

During the phone interview, participants were asked whether using any of the skills that they learned in the program helped them to avoid a crash. Of the 36 participants that said they used the skills that they learned in the program, 69% of those participants reported using the skills to avoid a crash.

Those who reported using the skills that they learned to avoid a crash were then asked to describe the skills that they used. Braking was the most frequent topical area, with responses such as “a car stopped right in front of me” and “a deer walked out in front of me.” Skid/drift was the second most common topical area with responses such as “letting off the gas” and “getting control of the car while hydroplaning.” Steering was the third most frequent topical area with responses, such as “someone veered into my lane on the interstate”. Other responses included “increased awareness” and “keeping control of the vehicle”. These topical areas are shown in Figure 20.

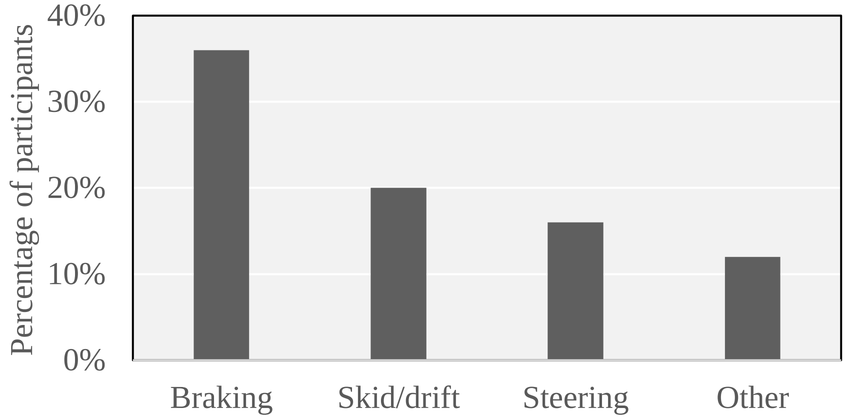


Figure 20. Topical areas for skills used to avoid a crash: phone interview.

3.3.6 Changes in Driving Behavior

During the survey, participants were asked whether they thought they will change their driving behaviors as a result of the program. Ninety-eight percent of the 134 participants felt that they would change their driving behaviors as a result of the program.

During the phone interview, participants were asked whether they changed any of their driving behaviors as a result of the program. Ninety-two percent of the 50 participants reported changing their behaviors as a result of the program.

Those that responded “yes” were asked to describe which behaviors they will change on the survey and which behaviors they did change during the phone interview. Response patterns from both the survey and phone interview were similar; see Figure 21. Reducing distractions was the most common topical area, followed by heightened awareness and driving position for both the survey and phone interview. Driving position included responses about seat adjustment, how to properly hold the steering wheel, and the process of getting prepared to drive a vehicle. Concerning the final four categories, there were differences observed between the survey and phone interview, where the survey responses focused more on the topical areas of both sight and being more careful/cautious, while the phone interview responses were focused on reducing speeding as well as paying attention.

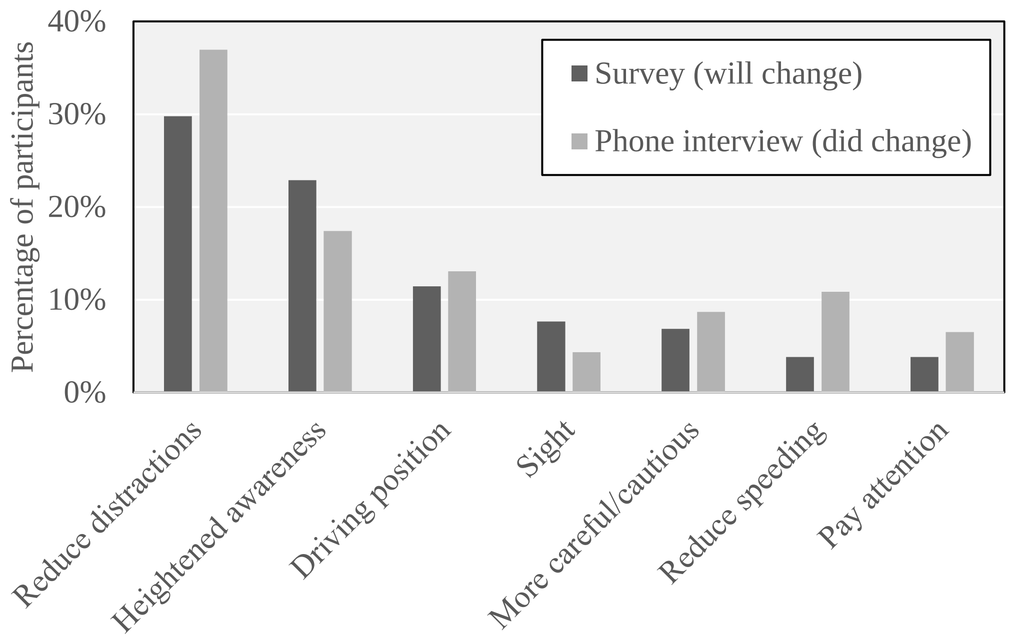


Figure 21. Topical areas for change in driving behaviors: survey vs. phone interview.

3.3.7 Rating the Program

During the phone interview, the participants were asked to rate the program based on how helpful and informative it was using a 1 to 5 rating scale, where 1 is “not at all” and 5 is “extremely”. All 50 participants provided responses ranging from 3 to 5, with an average response of 4.5. Fifty-two percent of the participants responded with a 5, 46% of participants responded with a 4, and 2% responded with a 3.

3.4. Discussion

The goal of conducting this study was to gain the teenagers’ perspectives of the half-day post-license advanced driver training program, Guard Your Life (GYL). This program begins in the classroom with an introduction to the professional driving instructors. The classroom portion includes instruction on the importance of knowing where to look, proper hand and seating position, mirror adjustment to minimize blind spots, oversteer and understeer corrections, the purpose of the anti-lock braking system (ABS), and the dangers of different types of distraction. The teenagers then get behind-the-wheel experience on a closed-road course with ABS braking, skid recovery and distracted driving. The teenagers complete a survey directly after the class and participate in a follow-up phone interview three months later.

The emergence of post-licensure driving courses (in the US), such as GYL, or multiphase driver's education (in Europe and Australia) have shown variation in effectiveness. Many international studies, particularly in Europe, before 1990 have shown adverse outcomes, suggesting that advanced driver training may cause higher crash rates (Katila, Keskinen and Hatakka, 1996; Lund and Williams, 1985; Mynttinen, Gatscha, Koivukoski, Hakuli and Keskinen, 2010). In order to address these findings, many European countries revised their respective programs to focus on insight and awareness training rather than skill mastery training to improve actual skills and shift perceived skills to match the driver's skill level (Washington, Cole and Herbel, 2011). In some European countries, including Sweden, Finland, Austria, Luxembourg and Norway, post-renewal training is required anywhere from 6 to 24 months after becoming licensed (Washington et al., 2011). Post-licensure training focuses on giving drivers an opportunity to learn their limits as well as the vehicles' limits by experiencing loss of control in the vehicle in order to develop necessary anticipation skills after becoming comfortable with driving basics. The benefits of implementing these programs resulted in a 9% reduction in overall crashes among teenagers in Austria over a five-year period, a 7% reduction in at-fault novice drivers in Finland over a six-year period, a 13% reduction in crashes among novice drivers in Luxembourg, and a 7% reduction in crash risk among first-year novice drivers in Denmark (Washington et al., 2011).

Though there has been some success with post-license advanced training courses, there is still much hesitation due to the claims that these courses increase young drivers' overconfidence. Training programs that only focus on maneuvering skills have been shown to increase driver's confidence further than their abilities. Though these drivers may know how to make the correct maneuvers, they may not know when to use the skills appropriately or what situations will require use of these skills (Beanland, Goode, Salmon and Lenné, 2013). This can be associated primarily with skid or slippery condition training. Gregersen (1996) performed a study comparing confidence between students who received skill-based training and those who received insight training in Sweden. The results showed an overestimation in slippery driving abilities from the skill-trained group not seen in the insight group, though both groups had similar performance on the task.

Though there is little evidence linking adverse effects of post-license advanced training due to overconfidence, it is possible that this contributes to the reason why many of these post-license advanced driving programs have not seen overwhelmingly positive effects. Katila, Keskinen, Hatakka, and Laapotti (2004) concluded that after participating in skid training, students showed increased confidence levels in their ability to drive in slippery conditions though there was no connection to changes in crash rates. In 1990, Finland introduced two-phase training, which included a skid-training course in the second phase. This course put more emphasis on anticipatory skills, making the maneuvering skills less important. When comparing the old curriculum (pre-1990) with the new, two-phase training (post-1990), the results indicate that drivers with the two-phase training had higher confidence levels in their slippery driving skills even though there was no difference in slippery crashes between the groups.

There have not been many post-license advanced training course evaluation studies conducted in the US. There are significant differences between licensing in Europe and the US. In Europe, there are several countries that have made the post-renewal training required. One of the biggest differences between the US and Europe is the licensing age. In Europe, the age to obtain a license is 18 years old, where in the US, the age a teenager can obtain a license varies, but is typically 16 years old. The requirements for passing an on-road driving test in the US focus on basic skills, not what a driver will do when confronted with an emergency situation when a crash is likely to occur (Fisher et al., 2016). Many other countries' process for obtaining a license requires a much deeper understanding and evaluation, such as the hazard perception test used in the UK, Netherlands and Australia, which have been shown to predict the crash risk of novice drivers (Fisher et al., 2016).

A recent US study from the Insurance Institute for Highway Safety (IIHS) (Farmer and Wells, 2015) evaluated a post-license course that consisted of skid avoidance and vehicle control. The course began with an explanation of vehicle dynamics and then the students got behind the wheel in a vehicle that allows for varying levels of reduced traction. The emphasis of the behind-the-wheel portion was to avoid the skid instead of making corrective actions to recover from it. The 234 students who took this post-license course were compared with a control group, and there were no significant differences in crash rates and moving violations between the groups. Both groups completed surveys that assessed confidence levels and perceived risk. The students were asked to rank their own driving skills and there were no significant differences in overall confidence between the groups. Another portion of the survey had the participants rank perceived risk associated with different situations, such as hard braking in snow and driving after dark. Participants that took the post-license course perceived driving in bad weather at higher risk than the control group, but they did not rate their own abilities as being higher than the other group.

For the survey and phone interview, the participants were not asked questions that specifically targeted overconfidence, but the survey completed immediately after the program showed that teenagers self-reported that they thought their most common changes in behavior would include reducing distraction, driving with a heightened awareness, and changing their driving position. The phone interview, completed three months later, showed that the most common self-reported changes in behavior were reducing distractions, having a heightened awareness, reducing speeding and changing their driving position. These changes suggest that the participants had an increased understanding of the dangers of driving both directly after the program and three months after the program—especially two of the greatest causes of crash fatalities of young drivers, speeding and distractions.

One of the critical differences between the studies mentioned (Katila et al., 1996; Lund and Williams, 1985) and the GYL program is the emphasis on the Electronic Stability Control (ESC) system. There is little evidence that the ESC system is discussed and used in the other driving programs. During the GYL program, this system is discussed during the classroom portion and the teenage drivers' experience the skid pad with the ESC system engaged before it is turned off to allow the drivers to feel the difference. This may help to discourage drivers from turning off the ESC system and understand what is happening with the ESC when it is engaged. In many of these other programs, it is unknown whether the vehicles used are equipped with ESC, especially in many of the earlier studies, because ESC was not required on vehicles in the

US until 2012 (NHTSA, 2007) and 2014 in Europe (European Parliament and Council, 2009). Having teenagers use new (2016 model year and newer), identical vehicles on each track exercise during the GYL program was beneficial because the teenagers all experienced the same vehicles with the same safety systems.

There are even fewer studies showing the effectiveness of ABS training. Petersen, Barrett, and Morrison (Petersen, Barrett and Morrison, 2006) conducted a study training students to use a two-phased braking strategy, where the students initially depress the brake pedal quickly, then steadily increase the pressure until the pedal is fully depressed. Though the students who received the training had smoother brake profiles and were less reliant on the ABS system, they took one car length longer to stop compared to the untrained drivers. A study by Mollenhauer, Dingus, Carney, Hankey and Jahns (1997) used a low-cost method of ABS training to evaluate whether that had any effect on ABS performance. A four-page pamphlet was read before driving on an icy track. The students who read the pamphlet had shorter stopping distances and more often used the correct activation technique. Unlike these two studies, the GYL program does not teach a two-phased approach—instead, GYL teaches teenagers to press the pedal as quickly and hard as possible in order to stop in the shortest distance possible.

Results from the phone interview show that ABS braking was the most used skill and the most used skill that helped participants to avoid a crash. Though ABS braking was not the most important skill that participants reported, it was the most frequently used skill after the program. Though the phone interview indicates that this skill was helpful to the participants, it does not indicate how effective the participants are at activating their ABS after the program.

3.5 Conclusion

The Guard Your Life (GYL) Challenge program is a non-profit, post-license teenage driving program founded by a family who lost their teenage daughter in a single-vehicle crash. The half-day driving program is taught by performance driving instructors, which includes both classroom and hands-on instruction on a closed-road track. In the classroom, the students and parents are introduced to topics ranging from different types of distractions, knowing where to look, proper hand and seating position, how to make corrections for oversteer and understeer, the purpose of ABS, etc. On the track, the students practice defensive driving skills including skid recovery and emergency braking as well as gain first-hand experience driving distracted.

The goal of this study was to evaluate the teenagers' views of the GYL program both immediately after the program using a survey as well as approximately three months later through a phone interview. During both the survey and phone interview, participants' responses reflected the overarching concepts that the teenagers were introduced to during the program, suggesting that participants of the Guard Your Life Challenge program gain the knowledge and skills introduced in the program both immediately upon completion and retain it up to three months later.

There are important differences in the participants' responses between the survey and phone interview (Table 6). When examining the key words used to describe the program, there was a shift from the survey results revolving around the emotional experiences of the program to the specific knowledge needed for safe driving in the phone interview. Sight or knowing where to look had a large presence on the survey results but was mentioned less frequently in the interview. The importance of understanding the implications of distractions increased from the survey to the interview.

Table 6. Summary of the five most common responses for questions on the survey, which took place immediately after the program, and the interview, which took place approximately three months later.

Question	When?	Most Common Responses for Each Survey and Interview Question				
Top five things you got out of the program	Survey	Braking	Distractions	Skid/drift	Sight	Safety
	Interview	Distractions	Braking	Skid/drift	Sight	Facts/stories
Key words to describe the program	Survey	Fun	Educational	Exciting	Awesome	Informative
	Interview	Fun	Educational	Helpful	Informative	Exciting
Most important thing you learned from the program	Survey	Skid/drift	Sight	Braking	Control/ recovery	Distractions
	Interview	Skid/drift	Braking	Distractions	Driving positions	Situations
Use of skills learned in the program	Survey	Emergency situations	Skid/drift	Braking	Every day	Distractions
	Interview	Braking	Skid/drift	Distractions	Safety	Sight
Skills to avoid a crash after the program	Interview	Braking	Skid/drift	Steering	Other	
Changes in driving behavior from the program	Survey	Reduce distractions	Heightened awareness	Driving position	More careful/ cautious	Reduce speeding
	Interview	Reduce distractions	Heightened awareness	Driving position	Reduce speeding	More careful/ cautious

The key "take away" from both the survey and the phone interview was the overall positive effect that the program had on the teenagers. The teenagers were introduced to defensive driving techniques that are not traditionally part of driver's education. In the US, driver's education courses rarely have the ability to practice ABS braking, skid recovery and driver distractions because, in order to practice these skills, a closed-road track with a large, wet surface is needed. Moreover, 72% of the interview participants reported using these skills within three months after the program. Of the teenagers that used the skills, 69% reported those skills helped them avoid a crash. The interview results suggest that participants benefitted from the defensive driving skills introduced in the Guard Your Life Challenge program.

3.6 Limitations

This study gave insight into the teenagers' views of the GYL program, but there were limitations. This study was a self-report survey. No performance data was collected, so it is unknown how well the teenagers were able to perform on each of the exercises and how performance during the program affected their driving and skills used after the program. It is also unknown when in that three-month period the teenagers reported using the skills that they were taught. The teenagers reported using the skills introduced in the class to avoid a crash. It is difficult to conclude whether the use of these particular skills was in fact due to an emergency situation. The GYL program is a half-day event, so only three different exercises were included. Full-day programs have the opportunity to offer additional exercises.

3.7 Future Research

Future research should aim to gain insight into parents' views of the class. Most of the parents stay for the entire program but are very attentive during the classroom portion of the program. Gaining parents' views could help to better understand what their teenagers got out of the class as well as whether they took anything away from observing. Future research should also explore teenagers' views from full- and multiday programs that include additional exercises.

As the automotive industry incorporates new technologies such as autonomous features, electrification, connected automated vehicles, vehicle infrastructure integration, etc., educational programs will need to prepare young drivers or passengers to use and understand these technologies. Future research should incorporate how to include these new technologies in teenage driving programs.

3.8 Practical Applications

The results of this study suggest that teenage drivers do not understand or have experience activating ABS. Some teenage drivers may be able to avoid crashes by practicing activating ABS. The results of this study were published in Safety as a journal article in September 2020 with the following citation: Mims, L., Brooks, J. O., Jenkins, C., Schwambach, B., & Gubitosa, D. (2020b). Teenage Drivers' Views of a Classroom and Closed-Road Post-License Advanced Driving Program, Guard Your Life. *Safety*, 6(4), 44.

CHAPTER FOUR: STUDY II - PARENTS' VIEWS OF A CLASSROOM AND CLOSED-ROAD POST-LICENSE DRIVING PROGRAM FOR TEENAGE DRIVERS, GUARD YOUR LIFE

The results of this study were published in Safety in December 2020 with the following citation: Mims, L., Brooks, J. O., Jenkins, C., Schwambach, B., & Gubitosa, D. (2020a). Parents' Views of a Classroom and Closed-Road Post-License Driving Program for Teen Drivers, Guard Your Life. *Safety*, 6(4), 56.

4.1 Introduction

In the US, parents are often vital to a teenager when developing driving skills and gaining driving privileges. Parents typically have a significant role in the responsibility of teaching their teens to drive. Once a teen is licensed, parents are responsible for setting boundaries and restrictions on their teens' driving privileges. The majority of research involving parents and their teen drivers has focused on these restrictions. With the emergence of post-license driving programs, it is unknown how parents view these programs or if there are benefits of parents attending these programs with their teen. The current study investigates a half-day program starting with a classroom portion, followed by an on-track portion, where the teens practice engaging the anti-lock braking system (ABS), recovering from a skid, and experience the dangers of driving distracted. The parents are strongly encouraged to attend the classroom portion and the majority stay to watch the track portion.

4.1.1 Parents' Role in Their Teen's Driving Experience

Parents typically play a critical role in their teens' driving development. Parents make important decisions that directly impact their teens' driving behaviors, from teaching their teen how to drive, to establishing boundaries and rules once the teen is driving independently to enrolling their teen in a post-licensure course.

For a teen that is under the age of 18, driver's education requires on average of six hours of driving time with a "professional" driving instructor, to gain basic vehicle maneuvering skills (Simons-Morton and Ouimet, 2006). As part of the graduated driver's license in many states, parents are required to provide about 50 hours of supervised practice with their teen driver (NHTSA, 2017a).

The majority of the teaching needed for independent driving is intended to be completed by the parents. This also means parents need to teach higher order skills like hazard detection and risk perception because teens will likely not have sufficient time with the driving instructor to develop these skills (Simons-Morton and Ouimet, 2006). Though teens need these higher order skills, little is known about what and how parents teach their teens to drive (Simons-Morton and Ouimet, 2006). A study conducted to gauge parent's views on implementing 50 hours of supervised practice showed that nearly all parents had a good experience with the graduated licensing program and most parents thought 50 hours was the right amount of practice (Waller, Olk and Shope, 2000). A study conducted by Mayhew, Simpson, and Pak (2003) showed that crash rates during supervised practice were much lower when compared to newly licensed teens driving independently.

If a teen driver has passed the on-road driver's test and is under the age of 18, many states grant licenses with restrictions. The restrictions vary by state but often include limitations on the number of passengers, curfew (NHTSA, 2017a), and/or cell phone use (Chase, 2014).

Restrictions target some of the most common causes for crashes. Driver error is the most common cause for teen crashes, especially distraction, which accounts for 9% of all teen crashes in the US (NHTSA, 2018a). Some of the most common types of crashes teens experience are single vehicle run-off-road crashes on both straight and curvy roads, rear-end collisions, and turning into an oncoming vehicle in an intersection (McDonald, Curry, Kandadai, Sommers and Winston, 2014). Acknowledging that the first few months after licensure produce the highest crash rates (Mayhew et al., 2003), most of the research involving teen driver's parents has focused on parents' perception of risk and the effects of establishing boundaries during the first months after licensure.

It has been shown that teens with parents who set stricter boundaries for their teen, including limiting teen passengers and nighttime driving, had lower crash and violation rates than teens with fewer restrictions (Simons-Morton, 2007). Unfortunately, most parents only set modest boundaries that last for a short period of time. Hartos, Eitel, Haynie, and Simons-Morton (2000) found that teen drivers who had their license for a year or more had fewer parental restrictions than those who had their license for less than a year. Even for parental restrictions lasting a year, these restrictions are often shorter than the duration of the restricted license period. Many parents fail to understand some of the greatest risks associated with newly licensed teens, like teenage passengers (Williams, Leaf, Simmons-Morton and Hartos, 2006). A study that interviewed teens and parents separately, showed the disconnect between the parents' and teens' expectations regarding driving privileges. The greatest disconnects between teens and parents were the expectations for the number of approved destinations, unlimited vehicle access, curfew and the number of teen passengers, where teens expected greater freedom and a lower number of restrictions than what their parents reported (Sherman, Lapidus, Gelven and Banco, 2004).

There is limited information on parent involvement on the first few months after licensure and even less information on parent involvement or parent perspective in post-license training focused on developing higher level skills.

4.1.2 Guard Your Life Challenge Program

The Guard Your Life (GYL) Challenge program was started by the Humphries family after they lost their teenage daughter, Victoria, in a single vehicle crash in July of 2012. She lost control of her vehicle at night and ran off the road, similarly to many other single-vehicle teen fatalities. The Guard Your Life (GYL) Challenge program (http://www.guardyourlifechallenge.com) is a non-profit, post-license driving program for teens. The program is held at a local performance driving center and focuses on introducing teens to emergency braking using ABS, skid recovery and the dangers of distracted driving (Figure 22).

Figure 22. Aerial view of the track with the locations of the 1 skid recovery, 2 ABS braking, and 3 distraction exercises indicated.

The program begins in the classroom before moving to exercises on a closed-road track. The parents are encouraged to stay for the classroom portion and the majority stay to watch the driving portion. The classroom portion consists of an introduction to the family and their story, followed by a spokesman from the state's Highway Patrol, who speaks about teen crash and fatality statistics. The officer gives a detailed explanation of the physics behind what happens to an individual's body and brain during a crash as well as the components of distracted driving NHTSA, n.d.). The spokesman often engages the parents in the discussion, so the parents acknowledge they are modeling driver distraction behaviors to their children (i.e., eating or drinking a beverage while driving, checking their phone for a work message) to demonstrate what a distraction is and how their behaviors can set poor examples for their teens.

Instructors from the performance center provide short introductions, including their years of experience and professional racing licenses held. The lead instructor then provides an overview of basic behaviors and adjustments needed for optimal positioning in the driver's seat. The instructor goes over the proper place to look out the windshield while driving as well as how to position the side and rearview mirrors to eliminate blind spots. Then, the instructor provides an introduction to the ABS that will be part of the emergency braking exercise, oversteer, understeer, and how to anticipate and make corrections in a loss of traction situation on the skid pad. The instructor finishes the classroom portion by giving an overview of the track and the three exercises. Next, the teens are divided into groups and rotate through the various exercises on the closed-road track (Figure 23).

(**a**) (**b**) (**c**)

Figure 23. (a) a teen driver learning how to recover from a skid, (b) a teen driver activating the ABS brakes, and (c) a teen driver completing the distraction exercise with an instructor on the track providing feedback.

A previous study examined the teens' views of GYL directly after the program through a survey and three months after through a phone interview (Mims et al., 2020b). The results from both the survey and phone interview reflected the overarching concepts the teens were introduced to during the program. The results from the survey showed that the teens learned about behaviors such as where to look while driving and proper seating positioning, as well as ABS braking and skid recovery. The results reported during the phone interview showed that 72% most of the participants used the skills on the road. The most common skills reported being used were ABS braking, skid recovery and reducing distractions. Half of the teens who completed the phone interview reported avoiding a crash using the skills taught, where ABS braking was the most common skill reported. Responses from the phone interview also suggest that 92% of participants reported changing their behaviors after the program. The most common changed behaviors reported were reducing distractions, driving with heightened awareness and changing their driving position. Overall, from the survey and phone interview the teens reported benefitting from the behaviors and skills introduced by the GYL program.

The GYL program encourages parents to stay for the classroom portion of the program. After observing how attentive the parents were during the classroom portion and the number of parents who stayed to watch the track portion, gaining the parents' views of the program was naturally the next step. For this follow-up study, teens and parents were recruited to participate in a survey that was completed after the GYL program to gain parent's perspective of the program, parents' beliefs on what they believed their teens gained from the program, and teen's perspective of the program for comparison purposes

4.2 Methods

4.2.1 Participants

Teen and parent participants were recruited after the completion of the previous GYL study with the teens (Mims et al., 2020b), from the eight following consecutive GYL sessions. Of the 225 teens from those eight sessions, 164 completed the survey. Teen participants included 91 males and 72 females with an average age of 16.4 years old, ranging from 15 to 19 years old (SD=1.06). A total of 134 parents completed the survey, including 60 males and 74 females. There were no identifiers on the surveys to link a parent and their teen together.

4.2.2 Procedure

Directly after the driving portion of the program, teens and parents return to the classroom for closing remarks and to complete the surveys. The surveys took between 10 and 15 minutes to complete.

Since the focus of this study was on the parents' perspective of their own behavior as well as that of their teen, the teens' survey data was used as a comparison. The survey questions for both the parents and teens are shown in Table 7. With the exception of yes / no questions, the majority of the questions were open-ended.

Table 7. Parent and teen survey questions. Words in italics show the questions that parents were asked to anticipate their teen's response. One asterisk (*) indicates questions that were only asked to four of the eight sessions.

Parent	Teen	Questions
	X	What is your age?
X	X	What is your gender?
X		Do you have any specialized training in driving?
X		Have you ever activated the ABS braking system while driving?

X		Have you ever experienced a skid?
X		Where you the primary teacher when your child was learning to drive?
X		Did you teach your child about ABS braking before today's program?*
X		Did you teach your child about recovering from a skid before today's program?*
X		Did you teach your child about distracted driving before today's program?*
X	X	Do you think you will change any of your driving behaviors as a result of the program?
X		Do you think your teen will change any of their driving behaviors as a result of the program?
X	X	What do you think were the top three things you learned from the program?
X		What do you think were the top three things your teen learned from the program?
X	X	What is the most important thing you (*and your teen*) learned?
X		What is the most important thing your teen learned?
X		Do you plan on discussing any of the topics that were discussed during the program with your teen?
X		After seeing the training your teen went through, would you consider additional driver's training for yourself?

4.2.2.1 Data organization

For each question, teen and adult responses were separated. Then all of either the teen or adult participants' responses were combined and sorted by grouping similar responses together. As the responses were sorted and grouped, categories were formed. These categories turned into topical areas, for example the topical area of ABS braking represents responses such as brake hard, stomp on the brake and emergency braking. The number of responses for each topical area were tallied to determine the most common responses. Then the topical areas were compared between the teens and adults.

4.3 Results

4.3.1 Parents' Driving Experience

4.3.1.1 Specialized driver training for parents

Parents were asked if they had any specialized driver training and 11% of the 125 parents that responded said they had specialized driver training. When asked what training they had experienced the most common responses were classes from BMW or similar defensive driving courses (36%), amateur and professional racing (21%), training through the DOT or DMV (14%), and 40 or more years of driving experience (14%).

4.3.1.2 Parents' experience with ABS

Parents were asked if they had ever activated ABS and 85% of the 119 parents that responded had experience ABS previously. When asked if they had been trained to activate ABS, 31% of the 128 parents had experienced training. Although only 20 of the 40 participants who said they had been trained to activate ABS, the most common responses for where or whom were you trained by were BMW (36%), father (18%) and reading about ABS (9%).

4.3.1.3 Parents' experience with skid recovery

Parents were asked if they had ever experienced skidding while driving and 92% of the 128 parents who responded had experienced skidding. Parents were also asked if they had been trained to recover from a skid, where 38% experienced training. Of the 48 participants who said they had been trained to recover from a skid 35 reported the place or person they were trained by. The most common places or people the parents were trained by were BMW (17%), a parent or family member (17%) and driver training (9%).

4.3.2 Parents Teaching Their Teens to Drive

4.3.2.1 Primary teacher when teen was learning to drive

Parents were asked if they were the primary parent when teaching their child to drive. Of the 134 participants, 133 parents responded either yes or no. Seventy-three percent of parents responded “yes” and 27% of parents responded “no”.

4.3.2.2 Parents teaching their teen about ABS

Parents were asked if they taught their child about ABS before the program. Of the 134 participants, 74 parents responded either yes or no. Fifty-three percent of parents responded “yes” and 27% of parents responded “no”. The parents who said they had taught their child about ABS, were asked to select the method they used. The options for method used were “discussion” and “hands-on practice”. Of the 39 parents who taught their teen about ABS, 30 parents selected a method. The majority (87%) had a discussion with their teen about ABS and 13% of parents responded with hands-on practice.

4.3.2.3 Parents teaching their teen about skid recovery

Next, parents were asked if they taught their child about skid recovery. Only 37% of the 73 parents who responded said they taught their child about skid recovery. When asked what method was used when teaching their child about skid recovery 25 of the 27 parents responded. The most common method used to teach their child about skid recovery was discussion (92%), where only 8% used a hands-on practice method.

4.3.2.4 Parents teaching their teen about distracted driving

Parents were also asked if they taught their child about distracted driving. Of the 74 parents who responded, 89% said they had taught their child about distracted driving before the program. The majority (96%) of the parents had discussions with their child about distracted driving, where few (4%) parents used hands-on practice.

4.3.3 Possible Changes in Driving Behavior as a Result of the Program

4.3.3.1 Parents' thoughts on possible changes in their own driving behavior

Parents were asked if they thought they would change their own behavior after observing the program. Of the 134 participants, 113 parents responded either yes or no. Eighty-one percent of parents responded "yes" and 19% of parents responded "no". Of the 92 parents that responded "yes", they were asked to indicate which behaviors they would change. Of the 77 parents that responded with a behavior, categories included: reduce distractions (31%), all / multiple behaviors (23%), skid recovery (8%, skid recovery is not a behavior but was among the top five responses given by parents), pay attention (7%), seat position (7%) and other (23%, all "other" topics were only mentioned by less than 5% of parents or only one parent).

4.3.3.2 Parents' thoughts on possible changes in their teen's driving behavior

Parents were asked if they thought their teen will change their driving behaviors as a result of the program. Of the 134 participants, 124 parents responded to this question, with 96% responding "yes" and 4% responding "no". For those parents who thought their teen would change their behavior, they were asked what behaviors they thought their teen will change. Of the 119 parents that thought their teen would change their behavior, 90 parents gave specific behaviors. Some of the most common responses were categorized into the following topical areas: reducing distractions (24%), more aware (14%), all / multiple topics (10%), look further ahead (9%), and more confidence (7%). The remaining 36% were "other" topics provided by less than 5% of parents or only one parent.

4.3.4 Top Three Things Learned from the Program

Both the teens and parents were asked to write the top three things that they had learned during the program. On the parent survey, parents were asked what they learned and what they thought their teen learned. There were 123 parents that gave responses for the top three things they learned, totaling 274 responses. Parents on average gave 2.0 responses with a range of one to three responses (SD=0.8). In total, 125 parents provided responses for the top three things they thought their teen learned, with a total of 275 responses. The average number of responses was 2.1, ranging from one to three responses (SD=0.8). A total of 160 teens responded, providing 465 responses. The average number of responses given by the teens was 2.8, with a range of one to three (SD=0.3).

The parents reported that the most important things they learned fell into the topical areas of: seat / hand position (22%), looking where they want to go (14%), braking (8%), skid recovery (8%), and distractions (8%). All "other" topics (40%) were mentioned by 5% or less of parents or one parent. Parents anticipated that their teen learned about the following topical areas: skid recovery (22%), braking (19%), distractions (14%), confidence (8%), and experience with unexpected situations (6%). The remaining "other" (31%) topics were mentioned by 5% or less of parents or one parent. Teens reported learning from the following topical areas: braking (20%), skid recovery (18%), distractions (17%), looking where they want to go (6%), and education (5%). The remaining "other" (34%) responses were mentioned by less than 5% of the teens or one teen. These results are shown in Table 8.

Table 8. Top three things learned for the parent's response, parent's anticipated response for their teen, and the teen's response.

Topics	Parent's response for self	Parent's anticipated response for their teen	Teen's response
Seat / hand position	22%	3%	2%
Look where want to go	14%	5%	6%
Braking	8%	19%	20%
Skid recovery	8%	22%	18%
Distractions	8%	14%	17%
Education	2%	0%	5%
Confidence	1%	8%	3%
Experience with unexpected situations	0%	6%	0%

4.3.5 Most Important Thing Learned from the Program

Participants on both the teen and parent surveys were asked to report the most important thing they learned during the program. On the parent survey, parents were asked what they thought their teen learned. In total, 121 parents and 155 teens responded. The most important things parents thought the teens learned include: skid control (18%), handling different situations encountered when driving (12%), ABS braking (12%), improved driving skills (10%) and distractions (9%). All "other" (39%) topics were mentioned by 7% or less of parents or one parent. Teens thought the most important things they learned fell into these topical areas: skid control (56%), ABS braking (16%), looking where you want to go (7%), distractions (7%), and staying calm (4%). All "other" (10%) topics were mentioned by 2% or less of teens or one teen. These results are shown in Table 9.

Table 9. Most important thing learned for parent's anticipated response for their teen and the teen's response.

Topics	Parent's anticipated response for their teen	Teen's response
Skid control	18%	56%
Handling different situations	12%	0%
ABS braking	12%	16%
Improved driving skills	10%	0%
Distractions	9%	7%
Look where want to go	6%	7%
Staying calm	3%	4%

4.3.6 Topics from the Program to Discuss with Teen After the Program

On the parent survey, participants were asked if they were planning on discussing any of the topics taught during the program with their teen in the future. Of the 127 parents that responded, 98% responded "yes" and 2% responded "no". The 125 parents who planned on discussing topics from the program were then asked which topics they planned on discussing. Of the 125 parents, 104 responded with a specific topic. The most common topics given were all / multiple topics (63%), reducing distractions (14%), skid recovery (6%), some parents wanted to ask their teen what they learned during the program (5%), and other (12%), mentioned by less than 5% of teens or one teen.

4.3.7 Additional Training

Parents were asked after watching their teens go through the program, if they, the parent, would consider additional training for themselves. Of the 115 parents that responded, 70% would consider additional training and 30% would not.

4.4 Discussion and Conclusion

The goal of conducting this study was to gain the parents' perspectives of the half-day post-license driver's training program, Guard Your Life (GYL). This program begins in the classroom with an introduction to the professional driving instructors. The classroom portion includes instruction on the importance of knowing where to look, proper hand and seating position, mirror adjustment to minimize blind spots, oversteer and understeer corrections, the purpose of the Anti-lock Braking System (ABS), and the dangers of different types of distraction. The teens then get behind the wheel experience on a closed-road course with ABS braking, skid recovery and distracted driving. Parents and teens completed a survey directly after the class to gain the parents' perspective in addition to the teens' perspective of the program. The inspiration for this study, came from observations of parents at previous GYL events, where the focus was only on the teens' view of the program (Mims et al., 2020b). During the classroom portion of the program, parents were engaged, and the majority stayed to watch the track portion of the program.

The results of the parent survey showed that most parents do not have specialized driver's training even though most parents have experienced ABS and a skid. When it came to teaching their teen to drive, about half of the parents taught their teens about ABS and even less taught their teen about skid recovery. Most of the parents reported talking to their teens about distractions. Though parents said they taught their teens about these topics, the overwhelming majority only had discussions with their teen.

The majority of parents thought they would change their behavior based on what they observed during the program including, reducing distractions, paying more attention and changing their seating position. These results show that the information from the classroom portion of the program may not have been known or incorporated into the parents' daily driving behaviors before the class. The behaviors the parents reported that they will change in the future are consistent with the behaviors the teens in the previous study reported changing three months after the GYL program (Mims et al., 2020b). This suggests that not only teens, but also parents can benefit from these types of programs.

In the US, the majority of the responsibility when it comes to teaching teens to drive falls onto the parents. Parents are models of behavior, so if a parent is driving distracted or in an incorrect driving position, it is possible the teen will exhibit the same behavior.

The results show that the majority of parents reported that after observing their teen complete the GYL program, they would consider additional driver's training for themselves. This may indicate that after observing the program, parents did not feel they were proficient in the skills taught in the program.

It is not clear exactly what parents teach their teens when learning to drive, but research suggests that parents typically focus on basic skills in controlled environments, not necessarily in the environments they will be driving in post-licensure (Mirman and Kay, 2012). It is unknown if parents teach these basic skills because they think they are the only necessary skills their teen needs to learn to drive or if it is because parents do not have the skills or resources to teach teens higher order skills.

4.5 Limitations

This study gave insight into the teens' and parent's views of the GYL program, but there were limitations. This study was conducted through self-report surveys. There was no performance data collected, so it is unknown if the teens or adults improved their driving skills. There was no follow-up after the program, so it is unknown if teens and parents actually changed their behavior or participated in additional training. The other limitation of this study is the parent population. Due to the fact that post-licensure training is not a requirement in the US, parents that sign their teen up for the GYL program are interested in having their teen become a safer driver, acknowledging additional training beyond driver's education may be beneficial. This view may not be consistent with all parents.

4.6 Future research

Future research should focus on incorporating follow-up surveys to determine if there were any long-term effects on the parents' behavior. In the future, it is also important to understand what parents teach their teens when learning to drive as well as why they teach their teens specific skills.

4.7 Practical Applications

The results of the study suggest that not only teens, but adults observing the program learned about ABS from the program. Understanding what ABS is, may not be common for all teen and adult drivers. The results of this study were published in Safety as a journal article in December 2020 with the following citation: Mims, L., Brooks, J. O., Jenkins, C., Schwambach, B., & Gubitosa, D. (2020a). Parents' Views of a Classroom and Closed-Road Post-License Driving Program for Teen Drivers, Guard Your Life. *Safety,* 6(4), 56.

Both teens and adult learned from the Guard Your Life Challenge program, consisting of three different exercises or topics. Though many of the teen and adult participants reported learning about ABS, the program only consisted of three different exercises. Chapter Five aims to explore if the claims of learning about ABS are consistent when more exercises are included during a full day post-license advanced driving class.

CHAPTER FIVE: STUDY III - TEEN AND ADULT DRIVERS' VIEWS OF A ONE-DAY CAR CONTROL CLASS ON A CLOSED-ROAD COURSE

The results of this study were published in Safety in December 2020 with the following citation: Mims, L., Brooks, J. O., Jenkins, C., Stronczek, A., Isley, D., & Gubitosa, D. (2020c). Teenage and Adult Drivers' Views of a One-Day Car Control Class on a Closed-Road Course. *Safety*, 6(4), 57.

5.1 Introduction

It is known that there are thousands of traffic related injuries and fatalities every year worldwide. Post-license advanced driver's training classes have emerged, with the goal of improving the skills needed to prevent and mitigate emergency situations. This study examines participants' attitudes immediately after one such post-license driving class, a one-day car control class (CCC), for teens and adults which aims to improve drivers' driving skills on a closed-road track.

5.1.1 Driver's Education and Licensing

In the US, an individual must obtain a license to drive independently. Most US states follow a graduated driver licensing (GDL) process, which consists of phases to help learner drivers gain experience before obtaining their driving independence. The first phase is the pre-driving phase, where individuals must pass a written exam testing knowledge of laws, policies and a vision screening (NHTSA, 2017a). Once the written knowledge exam is passed, individuals are granted a learner's permit, where they are able to practice driving when accompanied by an experienced adult driver, typically a parent. On average, learner drivers with permits are required to show 50 hours of documented accompanied driving time and some states require 10 hours of nighttime driving (Fisher et al., 2016). In some states, learner drivers under the age of 18 wanting to earn a license are required to take a driver's education course, typically comprised of 30 hours of classroom instruction and 6 hours of behind-the-wheel instruction (NHTSA, 2017a). After gaining experience during the learner driver phase, individuals then take an on-road test in order to earn a license and drive independently (Fisher et al., 2016). The on-road test varies by state, but often tests the driver's ability to drive with typical street traffic, while maintaining appropriate speed and lane positioning. The on-road test usually requires different vehicle maneuvers, like turning left and right, backing up, and parking (e.g., Florida Department of Highway Safety and Motor Vehicles, 2018; Georgia Department of Driver Services, 2018; State of California Department of Motor Vehicles, 2017; Texas Department of Public Safety, 2017). When a driver passes the on-road test and is under the age of 18, the driver has earned the ability to drive independently, but often has restrictions like a limited number of passengers and/or a curfew (Fisher et al., 2016).

Though there has been steady progress to improve the licensure process in the US, the requirements to gain a license in other countries, especially in Europe, are more stringent. In the majority of European counties, including all countries in the European Union (EU), individuals are not able to operate a motor vehicle independently until one is 18 years of age (European Union [EU], 2019). In the US, the average age to drive independently is 16, but is dependent on the state of residence, which ranges from 14 (South Dakota Department of Public Safety, 2018) to 17 years old (New Jersey Motor Vehicle Commission, 2019).

The EU has minimum standards for the written and on-road tests needed to obtain a license. However, with driver training and driving schools, the EU has no standards, and the requirements vary greatly by country. European countries are split in regard to their approach to driver's education; some countries require a single learning phase, while others have a two-phase licensing process. The single-phase model is similar to the GDL in the US, where the driver is required to have classroom and behind-the-wheel instruction before an on-road test and once the on-road test is passed, the driver can drive independently (Twisk and Stacey, 2007). The two-phased approach that Sweden, Finland, Austria, Luxembourg, and Norway, for example, typically use consists of a first phase, similar to the single phase for other EU countries, but also includes a second training requirement. The second requirement aims to further improve the driver's skills while addressing the overconfidence that can occur as a result of gaining more advanced skills. The second-phase behind-the-wheel instruction typically focuses on anticipation and accident-avoidance techniques in environments where loss of control is likely, for example when experiencing a skid on ice (Washington, Cole and Herbel, 2011).

One of the biggest differences between driver's education in the US versus European countries, is the permit or practice phase before obtaining a license. In the US, the majority of the practice a driver gains is from a nonprofessional experienced driver, typically a parent. In many EU countries, this practice is with a professional driving school, accompanied by a professional instructor (Keskinen and Hernetkoski, 2011). Since drivers in European countries are typically required to drive with a professional instructor, the number of hours for behind-the-wheel instruction is two to three times higher than the US requirement (Fisher et al., 2016; Keskinen and Hernetkoski, 2011).

5.1.2 Crash Statistics

5.1.2.1 US crash statistics

In 2017, there were 34,247 police-reported motor vehicle fatal crashes, 1,889,000 crashes that resulted in injury, and 4,530,000 crashes that caused property damage only. The fatality rates are higher for males than females in every age category. Across drivers' age groups, the distribution of fatality rates resembles a "U" with the highest rates for younger and older drivers. Drivers between the ages of 21-24 have the highest fatality rate (NHTSA, 2019a).

The critical reason for almost all crashes (94%) can be attributed to the driver (Singh, 2018). Driver error is responsible for most crashes and can be broken down into four primary categories: 41% caused by recognition errors (distractions, inattention and visual scanning errors), 33% to decision errors (driving too fast for road conditions, illegal maneuvers, misjudgment of other's actions or speed), 11% to performance errors (overcompensation, lack of control), non-performance errors (drowsy or sleep), and 8% to other reasons (Singh, 2018). The most common error, recognition errors, are typically attributed to distraction or inattention. Teenage drivers, ages 15 to 19, have the fewest number of total drivers yet the highest percentage of distraction or inattention of any age group, attributing to 8% of the fatal crashes in 2017 (NHTSA, 2019a).

For drivers of all ages, 57% of all fatal crashes were single vehicle crashes in 2017, making single vehicle crashes the most common fatal crash scenario in the US. Single vehicle crashes are often attributed to a collision with a fixed object (30%), which includes objects like trees or shrubbery (7.2%) and curbs or ditches (7.1%). Single vehicle crashes can also result from collisions with a not fixed object made up 22% of all fatal collisions, which includes collisions with pedestrians (16.2%). Another common fatal crash scenario is multiple vehicle crashes, which involve a collision with another vehicle (39%). The most common areas attributed to fatal multivehicle crashes with another vehicle were collisions at an angle (18.6%), head on (10.1%), and rear end (7.2%). Other fatal crashes that do not fit into the previous categories are classified as non-collisions (9%), which are mainly attributed to vehicle rollovers (8.0%) (NHTSA, 2019b).

When it comes to teenage drivers, though they only account for 5% (NHTSA, 2018c) of the total licensed drivers in the US, they are associated with a disproportionate number of traffic related injuries and fatalities. In 2017, drivers between the ages of 16-20 had the highest injury rate and second highest fatality rate of any other age group (NHTSA, 2019b). Driver error is the most common cause for teenagers being involved in crashes. Driver error consists of recognition errors (visual scanning errors, distraction), decision errors (following distance, vehicle speed relative to conditions), and performance errors (losing control) (Curry, Hafetz, Kallan, Winston and Durbin, 2011). The most common crash scenarios associated with teenage drivers involve vehicles running off the road, on straight and curved roads, rear-end crashes and turning into the path of an oncoming vehicle (McDonald, Curry, Kandadai, Sommers and Winston, 2014).

5.1.2.1 Crash statistics across countries

Traffic related deaths and injuries are a large issue in the US, but also worldwide. There are many differences in how drivers training is enforced, which shows when comparing the traffic related death rates. When compared to other high-income countries, the US has one of the highest death rates due to a vehicle crashes, 12.4 per 100,000 population. Many of the high-income European countries (2.7 to 9.7 per 100,000 population), Canada (5.8 per 100,000 population) and Australia (5.6 per 100,000 population) have much lower death rates compared to the US (World Health Organization [WHO], 2018).

5.1.3 Post-License Driving Programs in the US

Due to the high number of crashes in the US as well as the differences in driver's education programs between the US and European countries, many post-license driving programs have emerged. The programs vary drastically ranging from new driver safety courses to performance driving courses on racetracks. Though these courses serve different customers, there is a common goal to improve drivers' skills behind-the-wheel in a controlled environment. Typically, the aim of the programs for new drivers, focus more on safety than the adult programs, which are often designed to address performance driving.

Many of the post-license driving programs are focused on young drivers' safety due to the high crash rates associated with new drivers. The aim of the many of the post-license programs is to give young drivers behind-the-wheel experience in a controlled environment to enable the teenagers to learn how to use the vehicle's safety systems as well as the dangers of distracted driving. The programs for young drivers are offered by non-profits (https://www.guardyourlifechallenge.com/, https://putonthebrakes.org/), foundations (http://www.southmetrofoundation.org/136/Teen-Crash-Avoidance-Skills), private driving companies (https://www.drivesafer.com/courses/drive-safer-basic-car-control-and-defensive-driving-course/, http://www.birperformance.com/streetsmarts/), police or sheriff's departments (https://www.flsheriffs.org/law-enforcement-programs/our-programs/teen-driver-challenge), automotive manufacturers (https://www.drivingskillsforlife.com/), etc.

In terms of adult programs, safety is still a priority, but there is a typically a focus on performance driving that is not seen in the programs aimed at the young drivers. Many of the adult programs address accident-avoidance skills like skid control and braking using the anti-lock braking system (ABS), but also the basics of racing and often take place at racetracks (http://www.raceschool.com, https://midohio.com/mid-ohio-courses, https://www.amgacademy.com, https://bondurant.com/, https://www.skipbarber.com/, https://racenow.com/). The adult programs also offer other advanced driving courses to cater to those individuals focused solely on racing or the racing experience. Unlike the teenage classes, most of the available programs are offered by private driving or racing companies rather than foundations or police/sheriff's departments.

Even though post-license driving programs go beyond basic topics covered in driver's education and are believed to be effective to increase knowledge and a drivers' skills, there is limited data showing this trend.

5.1.3 Car Control Classes (CCC)

The car control classes (CCC) offered allow drivers of all ages to practice defensive driving skills through a variety of exercises on a closed-road course (https://bmwperformancecenter.com/). Separate teenage and adult car control classes (CCC) focus on teaching students skills to increase their ability to control the vehicle by gaining both classroom and behind-the wheel experience on a closed-road course. One and two-day entry-level classes are offered, where the two-day classes provide more practice. The focus of this research is exclusively on the one-day CCC. Each CCC is a full 8-hour day, with a maximum of 16 students and three instructors per class. The CCC begins with classroom instruction that lasts approximately ninety minutes. The classroom experience begins with instructor introductions including their professional driving experiences and credentials. Then the lead instructor provides information on proper seat and mirror adjustment as well as proper outward vision when driving, which includes how far to look ahead, where to look when turning and where to look during obstacle avoidance. Next, the instructor provides an overview of the morning driving exercises. Then the instructor explains the underlying vehicle dynamics associated with each exercise, for example, the forces the vehicle will experience during that exercise and how the vehicle reacts to the driver's actions.

The morning on-track instruction lasts approximately two hours, see Figure 24 for the track. While the order of the exercises differs between the teenage and adult classes, the overall purpose is identical. See Table 1 for the description and purpose of each exercise. During the on-track instruction the students receive continuous feedback from the instructor either over a two-way radio when the instructor is observing while standing next to the track or from the passenger's seat when the instructor is in the vehicle. In many exercises, the instructors provide feedback after the students make errors to help the student understand the difference between feeling the incorrect and correct action.

The afternoon session begins in the classroom for approximately 30 minutes where the lead instructor provides an overview of the afternoon exercises (see Table 10). Then the students return to the closed road course for the on-track instruction. The class concludes with a high-level recap of the day in the classroom.

Figure 24. Aerial view of the closed-road course.

Many of the teens' and adults' exercises overlap, with the exception of exercises that involve competition. The teens purposively do not compete with one another. The adults are given the option to compete to simulate added stress (and for some, excitement).

Table 10. Teen and adult CCC exercises, exercise description, and exercise purpose.

Teen	Adult	Exercise	Description	Purpose
X	X	1.Warm-up slalom	Weave through cones in slalom pattern	Importance of vision and steering technique, introduction to the vehicle
X	X	2. ABS braking	Activate ABS at varying speeds (30-55 mph) in a corner	Skills needed for a panic stop, brake and steer, proper vision
X	X	3. Skid pad	Experience understeer and oversteer with and without stability control	Identify understeer/oversteer and make the proper correction
X	X	4. Single lane change	Experience an abrupt lane change with ABS stop	Rapid steering needed in an emergency situation
X	X	5. Handling course	Weave through cones in a slalom pattern, turn and return through with ABS stop	Feel the traction limits while accelerating, braking and cornering
X		6. Challenge course	Obstacle course with braking, accelerating, lane change, slalom, and wet turn around	Combine skills taught, challenge drivers' judgment
	X	7. Autocross	Combine multiple skills like cornering, braking and vision on a curvy track with inclines/declines and slalom	Feel handling limits of the car, steering technique, largest radius with the least amount of steering, proper vision
	X	8. Rat race	Retain control on wet circular track without stability control, race other drivers	Feel traction limits, steering with little traction, braking and accelerating affects traction, pressure of competition
	X	9. Timed runs	Combine multiple skills like cornering, accelerating and braking on a curvy track while being timed	Combine skills taught, challenge drivers with time pressure

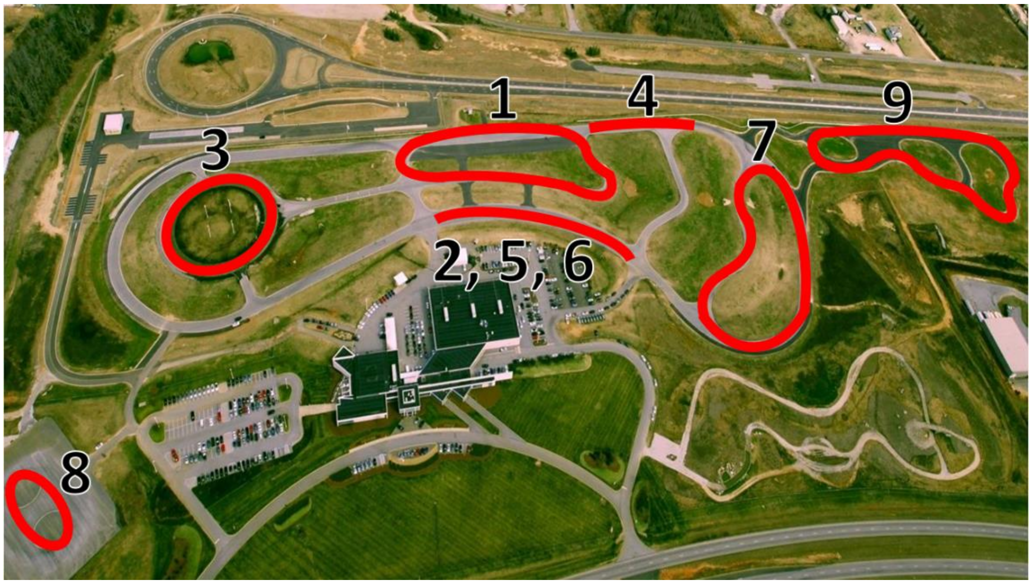


Figure 25. Locations of exercises on the closed-road track.

In a previous study, teenage drivers' views of a post-license half day driving program, Guard Your Life Challenge program, was evaluated (Mims et al., 2020b). Guard Your Life takes place at the BMW Performance Center, but focuses on three exercises, which include ABS braking, skid pad and a distraction task (not part of the CCC). Surveys immediately after the program, demonstrated that the teenage drivers benefited from the knowledge gained from both the in-class and on-road exercises. A follow-up phone interview conducted three months later, suggests that the teenage drivers used the skills from the program on the road and the teenagers felt they avoided crashes by utilizing the skills taught in the program. The CCC is a full day class, where drivers experience a larger number and more diverse exercises compared to Guard Your Life. The performance driving center has received anecdotal feedback from students from the CCC, but no formal evaluation has been conducted. The purpose of this study is to gain an understanding of teenagers' and adults' views of the CCC.

5.2 Methods

5.2.1 Participants

Participants were recruited from the teenage or adult one day car control classes over a 5-month period. For the teenagers, 80 participated, including 54 males, 25 females and 1 individual who did not identify their gender. The teenagers ranged in age between 15 to 18 years with a mean age of 16 years (SD=0.94). There were 30 teenagers with permits and 50 with either a restricted or a full license.

For the adults, 177 participated, including 137 males and 39 females. Ages ranged between 18 to 80 years with a mean age of 51.6 years (SD=16.2). There were 21 participants between the ages of 18 to 29, 20 participants between the ages of 30 to 39, 33 participants between the ages of 40 to 49, 35 participants between the ages of 50 to 59, 45 participants between the ages of 60 to 69, and 21 participants between the ages of 70 to 80.

All participants had the option to volunteer to be included in a follow-up phone interview approximately six months after the class. Unfortunately, there were very few teenagers that volunteered and as a result no follow-up phone interview data is presented for the teenagers. For the follow-up phone interview, 64 adults, including 46 males and 18 females, with a mean age of 51.5 years (SD=16.4) participated.

5.2.2 Procedure

All subjects read the consent form and provided their written approval prior to participating in the study. Since some of the participants were teenagers, all participants under the age of 18 years had written permission from a parent. The study was conducted in accordance with the Declaration of Helsinki and the protocol was approved by the Ethics Committee at Clemson University (IRB2015-258).

Both the survey and the phone interview each took between 10 and 15 minutes to complete. The survey took place immediately after the CCC was over while the phone interviews too place approximately six months after the class. The questions on the survey targeted the students' experience throughout the classroom and on-track instruction; the phone interview targeted the students' reflections on the class as well as behaviors or skills used while driving since the class. The majority of the questions were short answer that could be answered using a word or a short phrase (see Table 11). Additional sections of the survey and phone interview asked participants to use a numeric scale to respond to a list of various topics (see Rating Sections below).

Table 11. Survey and phone interview questions. The words in italics were used for the follow-up phone interview.

Teen Survey	**Adult Survey**	**Adult Phone Interview**	**Questions**
X	X	X	What is your age?
X	X	X	What is your gender?
X	X	X	What are the top three (*five*) things you got out of *(remembered from)* the class?
X	X	X	Describe the class in 3 words.
X	X	X	What is the most important or interesting thing you learned (*during the driving portion*)?
X	X	X	Would you recommend the class to your friends and family?
X	X		What was the hardest part about the class?
X	X		What did you enjoy most about the class?
		X	*Have you used any of the skills you learned in the class?*
		X	*Did using these skills help you to avoid a crash?*
		X	*Have you been in a crash since you took the class?*

		X	*Do you think you have changed any of your driving behaviors?*

5.2.2.4 Rating sections

The survey and phone interview included questions that asked participants to use a numeric scale to rate a given topic.

5.2.2.4.1 Frequency to exhibit behaviors from the class

The first rating section on the teenage survey, adult survey, and adult phone interview aimed to gauge how frequently the participants exhibited 17 behaviors taught during the classroom and behind-the-wheel instruction. Some examples include holding the steering wheel at 9:00 and 3:00, not driving distracted and looking where you want the car to go (see Table 4 in the Results section for all behaviors). Students used a 1 to 5 scale, where 1 was never and 5 was always, to describe how often they exhibited the behaviors. Participants could respond NS if they were not sure.

5.2.2.4.2 Competency level for on-track exercises from the class

The other rating section on the teenage and adult survey asked the participants to rate their competency to perform the seven exercises they experienced during the on-track instruction. Participants were asked to rate their competency level prior to the class and then their competency level immediately after the class. Participants used a 1 to 6 scale, where 1 was not competent to perform without extensive further training and 6 was fully competent to perform without further training.

5.2.2.5 Data organization and analysis

After the data were compiled, all of the responses for each question were sorted by grouping similar responses to form categories. For example, the ABS braking category represents responses like brake hard and stomping on the brakes. After the categories were finalized, the number of responses were counted, and the categories were compared.

5.2.2.5.1 Data analysis of frequency to exhibit behaviors and habits from the class

The teenagers' ratings from prior to the class were compared to their ratings after class using paired sample t-tests for each behavior to compare the rating from prior to and after the class. Unlike the teenagers, the adults had three different ratings (prior, after and six months after) and the ratings from the phone interview could not be matched to the survey. The analysis used for each behavior was a one-way analysis of variance, where the rating was the dependent variable and the independent variable was the time period of the rating, either prior to the class, after the class, or six months after the class. Once differences were found, Games-Howell post hoc analyses was used to find where the differences were. Since the teenagers and adults did not take the same class, ratings from the teenagers and adults were not compared.

5.2.2.5.2 Data analysis of competency level for on-track exercises from the class

Like the frequency exhibiting behaviors analyses, the teenagers' rating of their competency level from prior to the class were compared to their rating after the class using paired sample t-tests. Since the adults did not rate their competency level during the phone interview, the adults only have reported competency level ratings from the survey, the same analyses were used as the teenagers. As with the frequency exhibiting behaviors analyses, the teenagers and adults were not compared.

5.3 Results

5.3.1 Top Things from the Class

On the teenage and adult survey, participants described the top three things they got out of the class and on the adult phone interview they were asked to describe the top five things they remembered from the class, see Table 12. The teenage survey responses indicated that 72 of the 80 teenagers responded to this question for a total of 213 responses. The top three things the teenagers took from the class were skid control (18.8%), ABS braking (15%) and where to look when driving (9.4%). For the adult survey, 148 of the 177 adults responded for a total of 402 responses. These responses were similar to the teenage survey responses, where the adult survey's top three categories were ABS braking (17.2%), skid control (13.2%) and where to look (9.5%). For the adult phone interview responses, all 64 adult phone interview participants responded to this question for a total of 303 responses. The top categories from the top five things remembered from the class were ABS braking (14.2%), skid control (13.5), the instructors (9.2%), mirror adjustment (5.9%) and driving the vehicles (5.3%).

Table 12. Results for the top things from the CCC for the teen survey, adult survey and adult phone interview. TR equals the total number of responses for a group.

Topics	**Teen Survey (N=72 of 80, TR=213)**	**Adult Survey (N=148 of 177, TR=402)**	**Adult Phone Interview (N=64 of 64, TR=303)**
Skid control	18.8%	13.2%	13.5%
ABS braking	15.0%	17.2%	14.2%
Where to look	9.4%	9.5%	3.3%
Safety	4.7%	4.0%	1.0%
Fun	4.2%	7.0%	2.3%
Mirror adjustment	1.9%	2.7%	5.9%
Driving the vehicles	1.9%	1.2%	5.3%

Instructors	0.0%	0.0%	9.2%

5.3.2 Describe the Class in Three Words

Teenage survey, adult survey and adult phone interview participants were asked to describe the class in three words. Of the 80 teenage survey participants, 72 gave responses for a total of 210 responses for this question. The teenagers' top three words were fun (25.7%), educational (13.8%), and exciting (11%). For the adult survey, 149 of the 177 adults gave responses, for a total of 417 responses. The adult survey responses were consistent with the teenagers, where the top three responses were fun (25.9%), exciting (11%) and educational (9.4%). All 64 of the adult phone survey participants responded to this question, resulting in 190 responses. Two of the adult's phone interview responses were similar to the teenage and adult survey, where the top three responses were fun (16.3%), exciting (8.4%) in addition to informative (8.4%).

5.3.3 Most Important / Interesting Thing Learned

Participants from both surveys and the phone interview were asked what the most important or interesting thing was they learned from the class. During the phone interview, participants were asked to respond to this question specifically in terms of the experience on the track, unlike on the survey, which was more general. Of the 80 teenage survey participants, 73 provided responses. Their top three response categories were skid control or correction (34.2%), look where you want to go (17.8%) and emergency lane change (13.7%). For the adult survey participants, 146 of 177 provided responses. The most common response categories for the adult survey were skid control or correction (19.2%), ABS braking (12.3%) and looking where you want to go (12.3%). Of the 64 phone interview participants, 63 responded to this question. The top response categories for this question were ABS braking (23.4%), skid control or correction (19.2%), and three different for the third spot including emergency lane change (12.5%), controlling the car in different situations (12.5%) and the capability of the car (12.5%).

5.3.4 Hardest Part of the Class

Teenage and adult survey participants were asked what the hardest part of the class was. For the teenagers, 73 of the 80 participants gave responses and the most common response categories were emergency lane change (52.8%) and skid recovery (25%). Of the 177 adult participants, 143 gave responses for this question. The most common responses for the adult survey overlapped with the teenage survey responses, where the adults identified skid recovery (34.3%) as the hardest and emergency lane change (18.9%) as the second hardest part of the class. There was a large gap between the top two response categories and the other categories for both the teenage and adult survey.

5.3.5 Most Enjoyable Part of the Class

The teenage and adult survey asked what the most enjoyable part of the class was. Seventy-two of the 80 teenage survey participants responded to this question. Many of the teenagers either responded with "everything" or listed multiple exercises from the class, which were combined into everything/multiple exercises category. The most common response categories for the teenage survey were everything/multiple topics (19.4%), skid pad (19.4%), and handling exercise (18.1%). For the adults, 152 of the 177 participants gave responses, where the top response categories were timed laps (27.6%), instructors (10.5%) and everything/multiple (10.5%).

5.3.6 Frequency to Exhibit Behaviors from the Class

Throughout the teenage and adult CCC, participants were taught proper behaviors needed for driving, including topics like seating position, where to look, distractions, braking behavior, etc. Participants were provided with the list of behaviors taught in the class and asked to rate their frequency of the behaviors using the 1 to 5 scale, where 1 was never and 5 was always. Teenage survey participants were asked to rate their frequency of the behaviors prior to the class and after the class, see Table 13. The results from the repeated measures analysis of variance showed that there were significant differences between the teenagers prior and after rating on all behaviors. The results show that there were significant increases in the frequency the participants expected to exhibit the behaviors taught in the class from prior to the class to after the class.

Table 13. Teen survey participants' average rating of the frequency to exhibit behaviors prior to the class and directly after the class. The asterisk designates significant differences (p<0.05).

Behaviors - Teenagers	Mean Prior	Mean After	F	Degrees of freedom	η_p^2
Hold the steering wheel at 9:00 and 3:00 so that you can turn the steering wheel 180 degrees	3.04	4.53	122.850*	(1, 74)	0.624
Left foot on the dead/rest pedal	3.82	4.59	36.085*	(1, 75)	0.325
Adjust distance to pedals so that with the brake pedal fully depressed, you still have a bend in both legs	3.84	4.87	46.725*	(1, 73)	0.390
Adjust the seat height for proper outward vision (eyes are at the center height of the windshield or a hand width between the top of your head and the roof)	3.74	4.87	62.551*	(1, 75)	0.455
Position the back of the seat so you are sitting up straight	4.24	4.80	29.115*	(1, 75)	0.280
Position the seat close enough to where your hands can drape over the top of the	3.64	4.79	51.469*	(1, 69)	0.427

steering wheel without your shoulders pulling away from the seat					
Adjust the head restraint so that if you draw a line from your eyes through your ears, the part of your head touching the headrest lines up with the center of the headrest	3.09	4.39	67.628*	(1, 69)	0.495
Align the top curve of the steering wheel with the curve of the dashboard for a good view of the speedometer and gauges	3.49	4.46	46.966*	(1, 70)	0.402
Adjust the mirrors to eliminate blind spots	3.49	4.81	68.546*	(1, 73)	0.484
Keeping your eyes up to see far enough ahead	3.36	4.83	117.601*	(1, 76)	0.607
Look where you want the car to go	3.19	4.86	154.422*	(1, 76)	0.670
Turn your head to look where you want to go before you turn	3.56	4.80	99.133*	(1, 76)	0.566
Not drive distracted	4.33	4.70	18.335*	(1, 69)	0.210
Wear your seatbelt snugly	4.70	4.89	10.044*	(1, 69)	0.127
Use the brake pedal more proactively, especially in emergency situations	4.09	4.72	31.830*	(1, 68)	0.319
Not panic when you're in an emergency situation	3.47	4.47	55.857*	(1, 68)	0.451
Understanding the impact your driving can have on yourself and others	4.34	4.89	30.047*	(1, 69)	0.303

The results of the analyses of variance for the 17 different behaviors for the adults show that all were significant, with the exception of wearing the seatbelt snugly (see Table 14). The rating scores for wearing the seatbelt snugly were not significantly different from prior, after or six months after, but were near 5, so participants were already wearing their seatbelt snugly prior to and after the class.

The Games-Howell post hoc comparisons to reveal where the differences between the prior, after and 6 months after the class were, showed a general trend. The ratings given for prior to the class for all behaviors were significantly lower than the ratings given for after and six months after the class. There were few significant differences between the after and six months ratings, indicating that the frequency that the participants exhibited the behaviors from the class did not differ.

Table 14. Adult survey and phone interview participants' average rating of the frequency to exhibit behaviors prior to the class, directly after the class, and for the adults, 6 months after the class. The asterisk designates significant differences (p<0.05).

Behaviors	Survey		Phone interview	ANOVA results			Post hoc comparisons (mean differences)		
	Mean Prior	Mean After	Mean 6 months	F	Degrees of freedom	η^2	Prior to After	Prior to 6 months	After to 6 months
Hold the steering wheel at 9:00 and 3:00 so that you can turn the steering wheel 180 degrees	2.83	4.25	4.63	119.838*	(2, 367)	0.395	-1.420*	-1.797*	-0.377*
Left foot on the dead/rest pedal	3.87	4.47	4.47	15.320*	(2, 372)	0.076	-0.606*	-0.601*	0.005
Adjust distance to pedals so that with the brake pedal fully depressed, you still have a bend in both legs	3.54	4.74	4.52	60.039*	(2, 370)	0.245	-1.195*	-0.974*	0.221
Adjust the seat height for proper outward vision (eyes are at the center height of the windshield or a hand width between the top of your head and the roof)	3.67	4.72	4.68	54.849*	(2, 366)	0.231	-1.057*	-1.016*	0.041
Position the back of the seat so you are sitting up straight	3.89	4.63	4.44	27.047*	(2, 368)	0.128	-0.748*	-0.552*	0.196
Position the seat close enough to where your hands can drape over the top of the steering wheel without your shoulders pulling away from the seat	3.56	4.69	4.47	49.633*	(2, 364)	0.214	-1.128*	-0.907*	0.220
Adjust the head restraint so that if you draw a line from your eyes through your ears, the part of your head touching the headrest lines up with the center of the headrest	3.26	4.49	4.29	42.637*	(2, 353)	0.195	-1.228*	-1.021*	0.207
Align the top curve of the steering wheel with the curve of the dashboard for a good view of the speedometer and gauges	3.8	4.59	4.3	20.449*	(2, 363)	0.101	-0.796*	-0.498*	0.298
Adjust the mirrors to eliminate blind spots	3.46	4.78	4.7	73.851*	(2, 365)	0.288	-1.322*	-1.248*	0.074
Keeping your eyes up to see far enough ahead	3.6	4.76	4.72	94.183*	(2, 364)	0.341	-1.158*	-1.115*	0.043
Look where you want the car to go	3.25	4.74	4.69	144.748*	(2, 364)	0.443	-1.485*	-1.433*	0.052
Turn your head to look where you want to go before you turn	3.36	4.68	4.46	87.039*	(2, 364)	0.325	-1.318*	-1.100*	0.218
Not drive distracted	3.62	4.33	4.13	21.481*	(2, 349)	0.110	-0.715*	0.509*	0.206
Wear your seatbelt snugly	4.78	4.87	4.78	1.112	(2, 349)	0.006	-	-	-
Use the brake pedal more proactively, especially in emergency situations	3.68	4.73	4.47	66.378*	(2, 341)	0.280	-1.052*	-0.793*	0.258
Not panic when you're in an emergency situation	3.68	4.52	4.48	38.098*	(2, 326)	0.189	-0.844*	-0.800*	0.044
Understanding the impact your driving can have on yourself and others	4.14	4.74	4.44	20.271*	(2, 345)	0.105	-0.606*	-0.298*	0.307*

5.3.7 Competency to Perform Class Exercises

The teenage and adult CCC offer a variety of exercises that target different skills. Many of these exercises overlap between the teenage and adult classes, but they are slightly changed for the appropriate group. The teenagers and adults were asked to rate their competency to perform the exercises from the class, both prior to the class and after on the survey. Participants were to respond using the 1 to 6 scale, where 1 was not competent to perform without extensive further training and 6 was fully competent to perform without further training. The results from the repeated measures analysis for the teenagers, showed that there were significant increases in the competency ratings from prior to the class to after the class (see Table 15). Similarly, the results from the repeated measures analysis for the adults showed that there were significant increases in competency ratings from prior rating to the after rating.

Table 15. Teen and adult survey participants' average rating of their competency to perform the class exercises prior to and directly after the class. The asterisk designates significant differences (p<0.05).

Exercises	Teen survey					Adult survey				
	Prior	After	F	Degrees of freedom	η_p^2	Prior	After	F	Degrees of freedom	η_p^2
Accurately driving through the slalom course	3.03	5.44	280.860*	(1, 69)	0.014	3.33	5.14	343.973*	(1, 141)	0.007
Stomping on the brakes to feel the ABS activate	3.23	5.63	186.968*	(1, 69)	0.014	3.64	5.42	270.669*	(1, 143)	0.007
Understand how ABS allows you to steer and brake simultaneously	2.84	5.53	297.552*	(1, 69)	0.014	3.45	5.34	325.167*	(1, 142)	0.007
Controlling a skid	2.07	4.92	357.708*	(1, 69)	0.014	3.02	4.89	391.048*	(1, 144)	0.007
Identifying understeer (front tires have lost grip) and correcting for it	2.04	5.01	453.956*	(1, 69)	0.014	2.91	4.86	372.224*	(1, 143)	0.007
Identifying oversteer (rear tires have lost grip) and correcting for it	2.11	5.01	337.658*	(1, 69)	0.014	2.93	4.85	366.047*	(1, 143)	0.007
Making an emergency lane change	2.07	4.81	379.070*	(1, 69)	0.014	3.03	4.90	419.646*	(1, 143)	0.007
Completing the handling course	2.86	5.32	305.725*	(1, 68)	0.014	2.96	4.98	400.477*	(1, 140)	0.007
Completing the challenge course	2.45	5.09	339.962*	(1, 68)	0.014	-	-	-	-	-
Completing the autocross course	-	-	-	-	-	3.00	5.01	373.496*	(1, 142)	0.007
Completing the timed lap	-	-	-	-	-	3.00	4.88	319.118*	(1, 136)	0.007

5.3.8 Skills Used After the Class

The adults who participated in the phone interview were asked if they had used any of the skills they learned in the class. All 64 participants provided a response for this question. Within six months of the class, 77% of the participants reported to using skills they learned. Those individuals who reported to using the skills were asked a follow-up question to describe which skills they had used. A total of 49 participants gave responses for this question where the most common response categories were multiple skills (34.7%), ABS braking (22.4%), seating/hand/mirror position (20.4%) and where I look (14.3%).

4.3.8.1 Skills used to avoid a crash after the class

The 49 of the participants that said they had used the skills taught in the class were also asked if using any of these skills helped them to avoid a crash. Of the 48 participants that responded, 23% indicated that the skills helped them avoid a crash. The participants that said the skills that helped them avoid a crash were then asked which skills they used. The majority of participants used ABS braking (81.8%) to avoid a crash. The other common responses were skid recovery (9.1%) and braking and steering (9.1%). Four of the participants who responded "yes" did not give a skill, but rather provided responses like "maybe" and "not yet", therefore their "yes" was not included in the crash response percentages.

5.3.9 Behaviors Changed After the Class

The adult phone interview asked if they changed any of their driving behaviors as a result of taking the class. All 64 participants gave a yes/no response and 95% responded with "yes" they had changed their behavior. Those who responded "yes" were asked a follow-up question where 61 participants gave a specific behavior, with some of the most common response categories being seating/hand/mirror position (26.6%), where I sit in combination with where I look (21.3%), where I look (16.4%), following distance (8.2%), and where I sit in combination with braking (6.6%).

5.3.10 Class Recommendation

The last item on the teenage survey, adult survey and adult phone interview asked if the individual would recommend the class to others. A total of 154 teenagers responded with 100% responding “yes” to recommend the class. For the adult survey participants, 72 gave responses, with 99.4% responding “yes”. Finally, 61 of the adult phone survey participants responded and 93.8% said “yes” they would recommend the class to others.

5.4 Discussion

Car control classes (CCC) offered at a performance driving center provide drivers classroom and on-track instruction that focuses on practicing defensive driving skills on a closed-road course. The students gain exposure to correct seating position, mirror placement, where to look as well as the vehicle’s behavior throughout the exercises experienced during the on-track instruction. The on-track instruction consists of multiple exercises, each focusing on different maneuvers (ex. emergency lane change) and utilizing various vehicle safety systems (ex. ABS and stability control). The goal of this study was to gain an understanding of the teenagers’ and adults’ views of the car control class (CCC). Teenage and adult participants completed a survey directly after the class to document their immediate perspective of the course and a subset of the adults completed a six-month follow-up phone interview.

The results from the teenage survey showed that the top three things the teenagers took away from the class were skid recovery, ABS braking and looking where you want the car to go.

Teenagers thought skid control, looking where you want the car to go and the lane change were the most important or interesting topics they learned about, even though the lane change and skid recovery were rated as the hardest parts of the class. The teenagers reported enjoying everything or multiple topics as well as the skid pad and handling exercises. Interestingly, the teenagers thought that the skid recovery and lane change exercises were the most important, hardest and most enjoyable. There were significant increases in the frequency of predicted use of the behaviors taught in the class, from sometimes to almost always. There were also significant increases in the competency, where teenagers on average reported feeling moderately competent to perform the exercises after the class. Overall, the teenagers reported learning and improving their driving skills as a result of the class.

The adult survey results also showed the top three things the adults got out of the class were skid recovery, ABS braking, and looking where they want the car to go. The most important things the adults reported learning were skid recovery, ABS braking and looking where they want the car to go. The skid recovery and lane change were reported as the hardest parts of the class. The adults reported that they enjoyed everything or multiple parts of the class as well as the instructors and the competitions they experienced during the timed laps. There were significant increases in most of the adults' frequency to exhibit certain behaviors from prior to after the class, from sometimes to almost always. There were also significant increases in the adults' competency rating from prior to after the class, where the adults on average reported feeling moderately competent to perform the exercises after the class.

The phone interview conducted six months after the participant took the CCC, targeted the participant's experience with the skills and behaviors taught during the classroom and behind-the-wheel instruction. Participants reported the top things they took away from the class were skid recovery, ABS braking and interacting with the instructors. The most important topic they reported learning about was ABS braking, skid control, lane change, controlling the car in different situations, and the capability of the car. The results also showed significant increases in the frequency of use of the majority behaviors from the class from prior to the class to six months after. There were also not many significant differences between the frequency of use of the behaviors rated after the class on the survey and six months after the class, indicating that the adults accurately predicted their use of the behaviors and turned those behaviors into habits.

The majority of the participants reported using the skills taught during the CCC in the previous six months. The most used skills that participants reported were ABS braking, looking where they want the car to go, seating position and mirror position. The skill used most to avoid a crash was ABS braking.

Almost every adult phone interview participant reported changing their behaviors as a result of the class, and the behaviors they reported overlapped with the skills they reported using, like seating position, where to look, mirror position, etc. The difference from the reported skills used to the reported behaviors changed in terms of braking, shifted focus from activating ABS to increasing their following distance and using the brake more proactively. These results show that the adult phone interview participants gained knowledge from both the classroom and behind-the-wheel instruction.

There were many similarities between the teenage and adult survey responses. Both teenage and adult survey participants reported that the top three things they took from the class were skid control, ABS braking and where to look. The teenagers and adults agreed that skid recovery and looking where they want the car to go were some of the most important things they learned from the class. Both groups also reported that the skid recovery and emergency lane change exercises were the hardest parts of the class. Teenage and adult survey participants both thought skid recovery was one of the most important skills they learned even though it was difficult. The same trend was seen in the teenage and adult responses for the frequency they would exhibit the behaviors taught in the class. Many thought prior to the class sometimes they exhibited those behaviors, but all of the responses increased to almost always. Similarly, teenagers and adults both rated their competency to perform the exercises from the class as not competent prior to the class and then as moderately competent on most responses after the class.

There were also many similarities between the adult survey and phone interview. The majority of the responses for the frequency to exhibit the behaviors from the class followed the same trend as the survey, where the rating after the class was significantly higher than the prior. The frequency to exhibit the behaviors in the class responses were mostly significantly higher than the prior to the class rating from the survey. There were not many significant differences between the frequency responses after the class from the survey and six months after on the phone interview. This shows that adults accurately predicted how frequently they would exhibit the behaviors and actually exhibited the behaviors while they were driving. The most used skills that phone interview participants reported were ABS braking, looking where they want the car to go, seating position and mirror position. The skill used most to avoid a crash was ABS braking. These reported uses of the skills overlap with what the adult survey participants reported as being the most important skill learned from the class.

Though there were many similarities between the teenagers' and adults' survey responses, there were differences between the groups. Though both groups reported the same top three items they got out of the class, this was not the case when asked what the most important thing learned in the class. Both groups agreed on skid recovery and looking where you want the car to go, but the teenagers reported lane change much higher than the adults, who reported ABS braking much higher than the teenagers.

The top two responses for the most enjoyable part of the class from the teenage survey, skid pad and the handling exercise, both involve large steering inputs compared to many of the other exercises. The adults enjoyed the competition aspect of the timed laps and the instructors. Unlike the teenagers, the adult survey participants did not enjoy the hardest rated exercises.

There were some differences between the adult survey and the phone interview. When asked what the most important thing was learned, the adult survey participants' response categories of skid control and ABS braking overlapped with the phone interview response categories, but other top response categories did not. The other most common response category given by the adult survey participants, was looking where you want to go, where the other common response categories for the adult phone interview were the emergency lane change, controlling the car in different situations, and the capability of the car. The adult phone interview responses overlapped with the adult survey responses, but some of the responses were focused on the bigger picture of driving as a whole, rather than an individual skill or exercise.

Almost every adult phone interview participant reported changing their behaviors as a result of the class, and the behaviors they reported overlapped with the skills they reported using, like seating position, where to look, mirror position, etc. The difference from the reported skills used to the reported behaviors changed in terms of braking, shifted focus from activating ABS to increasing their following distance and using the brake more proactively. These results show that the adult phone interview participants gained knowledge from both the classroom and behind-the-wheel instruction.

Seating position was one of the most common responses when participants were anticipating what behaviors they would change and behaviors they had changed after the class. These results suggest that teenage and adult drivers do not understand how to position themselves properly in a vehicle. This is consistent with observations made by McConomy (2015), who showed that many younger and older adults do not position themselves correctly in a vehicle seat in order to have proper line of sight and the ability to reach the pedals.

One of the biggest differences between the teenagers and adults was their responses when asked what the most important thing they learned during the CCC. The teenagers thought the skid recovery and the emergency lane change were the most important exercises, where the adults thought the skid recovery and ABS braking were the most important. Though teenagers and adults both reported skid recovery as being one of the most important skills taught, the teenagers thought the most important exercises were the hardest to perform, not necessarily what they may use the most. The adults were able to acknowledge that ABS braking was one of the most important skills learned in the class, but it was important because it would be used, not because it was the hardest. This observation by the adults is consistent with common crash scenarios. In 2016, National Highway Traffic Safety Administration (NHTSA) reported one of the most common fatal crash scenarios was a rear end collision (NHTSA, 2018b).

The high response rate of ABS braking on the most important thing learned for the adult survey and phone interview participants, suggests that adults did not have prior knowledge or experience using ABS. This observation is consistent with results from a phone survey conducted by the NHTSA. The study sought to gain US drivers’ knowledge of ABS by asking questions about what ABS was and the purpose of the system. The majority of the participants did not know what ABS stood for, the advantages of having ABS over standard brake systems, and that it is normal for the pedal to vibrate (Mazzae, Garrott, & Snyder, 2001).

5.5 Conclusions

Car control classes offered to teenagers and adults focus on improving the drivers' knowledge and their ability to control a vehicle through classroom instruction and behind-the-wheel experience on a closed road course. Students of these classes gain knowledge about proper seating position, proper outward vision, vehicle safety systems, and vehicle dynamics in the classroom. Once behind the wheel, students experience various exercises focused on proper use of vehicle safety systems (ex. ABS), steering techniques (ex. lane change), and corrective maneuvers (ex. skid recovery). This study aimed to gain the views of teenagers and adults that participated in the car control classes. Teenagers and adults participated in a survey directly after the class and adults participated in a follow-up phone interview. The results from the teenage and adult survey show that both groups reported learning new behaviors and skills as a result of the class. The results from the adult phone interview show that participants reported changing their driving behaviors and using the skills taught during the class. These self-report results suggest that both teenagers and adults benefitted from the car control class.

5.6 Limitations

The surveys and phone interview gave insight into the teenagers' and adults' views of the car control classes, but there were limitations of the study. The surveys and phone interview were all self-reported. There was no performance data collected, so it is unknown how well the teenagers and adults were able to perform each exercise and how their performance affected their driving skills after the class. With the phone interview, it is unknown when in the six-month period the adults used the skills that they reported using. It is also difficult to conclude if the skills the adult participants reported using to avoid a crash were in fact needed to be used due to an emergency situation.

5.7 Future Research

Future research should strive to evaluate the effectiveness of the program from an objective perspective in addition to the survey data gathered during this study. Future research should address the effects of teaching teenagers and adults about stability control and ABS, but also how understanding these systems affects driving behavior.

5.8 Practical Applications

The results of this study suggest that both teenagers and adults learned about ABS during the CCC. The adults reported activating ABS after the CCC and in some cases to avoid a crash. Adults and teens may not have knowledge or experience with ABS, but it may be necessary to avoid crashes. The results of this study were published in Safety as a journal article in December 2020 with the following citation: Mims, L., Brooks, J. O., Jenkins, C., Stronczek, A., Isley, D., & Gubitosa, D. (2020c). Teenage and Adult Drivers' Views of a One-Day Car Control Class on a Closed-Road Course. *Safety*, 6(4), 57.

The results from the survey study of the car control class are consistent with the observations from the survey studies on the Guard Your Life Challenge Program for both teens (Chapter Three) and parents (Chapter Four), where ABS was one of the most important topics and most used skills on the road. Chapter Six narrows focus exclusively to the ABS exercise and drivers' performance activating ABS.

CHAPTER SIX: STUDY IV – DO HIGH SCHOOL STUDENTS HAVE KNOWLEDGE OF AND/OR EXPERIENCE USING AN ANTI-LOCK BRAKING SYSTEM?

6.1 Introduction

To determine novice drivers' knowledge and experience using ABS, it is necessary to explore drivers who have completed a driver's education course, where they may have learned about ABS. While high school students often complete driver's education, previous research suggests that even though high school students receive instructional information about ABS, these novices, teen drivers may not have an understanding or experience using ABS.

Mims et al. (2020b) investigated teenage drivers' views of a half day defensive driving program, the Guard Your Life Challenge. During the program, teen drivers drove while experiencing ABS braking, skid recovery and distracted driving. The course allowed the teens to practice activating ABS on a closed-road tack, braking from speeds ranging between 30 to 60mph. Directly after the program 134 teens completed a survey and 50 teens completed a phone interview three months later. The results of the survey identified ABS braking as one of the most important topics learned as well as one of the skills they predict using on the road. The results of the phone interview showed that the teen drivers reported ABS braking as the most used skill on the road and the most used skill to avoid crashes on the road after the program. The results suggest that teen drivers may lack knowledge of and experience using ABS.

Another study by Mims et al. (2020c), captured adult drivers' views of a full day car control class. The class consisted of eight different on-track exercises, including the same ABS braking exercise from the Mims et al. (2020b) study with teen drivers. One hundred and seventy-seven adults participated in a survey directly after the class and 64 adults completed a phone interview six months after the class. The results of the survey showed that adults identified ABS as one of the most important topics. The drivers indicated that their ability to stomp on the brakes to feel ABS activate as well as their understanding of the benefits of ABS such as the ability to steer and brake simultaneously, were improved as a result of the class. For the phone interview, ABS braking was one of the most used skills on the road and was the most used skill to avoid a crash. Like the teen study (Mims et al., 2020b), the adult drivers may also lack knowledge of and experience using ABS (Mims et al., 2020c).

To investigate driver's experiences and expectations of vehicles with ABS, NHTSA conducted a national phone survey as part of the Light Vehicle ABS Research Program in 1999 (Mazzae, Garrott, & Snyder, 2001). A total of 3,508 drivers over the age of 16 participated in the phone survey. The results of the survey found that 38.8% of participants knew that ABS stood for anti-lock braking system and 39.2% knew the advantages of ABS were to prevent the wheels from locking up and the resulting skidding. Forty-six percent of participants thought there would be something wrong with the vehicle if the brake pedal was to vibrate during braking, which is the feedback the driver receives during ABS activation. For the 47% of participants that reported having a vehicle equipped with ABS, 57.8% of those participants had felt ABS activate on their vehicle. For the participants that had not activated ABS on their ABS-equipped vehicle, 26% reported activating ABS on another vehicle. Though about 40% of the participants reported activating ABS either on their ABS equipped vehicle or another vehicle, 66% of the participates that had activated ABS had a vehicle equipped with ABS. In 1999, when ABS was a new technology, drivers typically learned about ABS when purchasing a new vehicle equipped with the technology (Mazzae, Garrott, & Snyder, 2001). The results of this survey indicated that many drivers did not have knowledge of ABS, even in 1999 when ABS was a targeted technology for marketing new vehicles (e.g., https://www.youtube.com/watch?v=-YlZXdQlgrI).

The national phone survey was conducted over twenty years ago. The amount of technology on vehicles has rapidly increase in that time period, for example, modern vehicles offer driver assistance technologies including lane warning departure, adaptive cruise control, collision avoidance and mitigation systems (Bengler et al., 2014). Thus, ABS is no longer a focus when marketing new vehicles, and drivers can no longer rely on the vehicle purchase experience for information about ABS.

Since ABS has been equipped on vehicles since the mid-1980s, ABS has been included as a topic in the education process of new drivers. In the US, teen drivers under the age of 18 wanting to obtain a license to drive independently, often complete a driver's education course to gain knowledge and experience (NHTSA, 2017a). Today's typical driver's education courses require 30 hours of classroom instruction, six hours of in-vehicle behind the wheel instruction and six hours of in-vehicle observation as a passenger (NHTSA, 2017a). The Novice Teen Driver Education and Training Standards (NTDETAS) serve as a guide for driver education courses in the US, but they are not requirements to be followed by every state (NHTSA, 2017a). ABS falls under the category of a vehicle technology system. The NTDETAS outlines that teen drivers should be able to identify and understand the purpose, benefits and limitations of vehicle technology systems, as well as recognize, observe and properly use vehicle technology systems (NHTSA, 2017a). In some states as part of the requirement for a driver under the age of 18 to obtain a license, teen drivers must also show documented supervised practice driving outside of driver's education. The hours required vary by state but generally consist of 50 hours and some states also require 10 hours of nighttime driving (Fisher et al., 2016).

Though knowledge and experience with ABS is outlined in the NTDETAS and could be addressed by the adult(s) responsible for supervised practice, ABS knowledge is rarely tested. The driver's licensure exam varies by state, but there is no requirement for ABS activation during the licensure test (e.g., Florida Department of Highway Safety and Motor Vehicles, 2018; Georgia Department of Driver Services, 2018; State of California Department of Motor Vehicles, 2017; Texas Department of Public Safety, 2017). Driving tests in some states may ask drivers to stop quickly, but there is no mention of an emergency stop where ABS activation is required (e.g., Florida Department of Highway Safety and Motor Vehicles, 2018; Texas Department of Public Safety, 2017).

Knowing that drivers rely on the information from driver's education and the adult(s) supervising driving practice, the purpose of this study was to investigate if driver's that have taken driver's education recently, have knowledge of and/or experience using ABS.

6.2 Methods

6.2.1 Participants

Participants were recruited from five high school physics classes, both advanced and standard classes. Physics classes were selected since the students who take this course are typically upperclassmen and are old enough to drive. In exchange for participation, students were offered extra credit, which was determined and provided by each teacher. All students in the classes were eligible for the extra credit, though responses from students without a permit or license were not included in the results. There was a total of 106 students that participated in the survey; after removing those individuals without a license or restricted license, individuals who did not complete the entire survey, or who did not attempt to give logical responses, a total of 60 participants' data were analyzed. The average age of the participants was 16.9 years ranging from 16 to 18 years (SD=0.48), with 50 seniors and 10 juniors. There was a total of 41 males and 19 females. Seven students had restricted licenses and 53 had full licenses. Of the 60 participants, 37 reported that they had completed driver's education.

6.2.2 Survey

In order to gauge high school students' knowledge of ABS, a survey was created. The survey consisted of background questions targeted basic demographic information including age and gender. The next set of questions targeted participant's knowledge and experience using ABS. See Table 16 for background questions and ABS related questions.

Table 16. Background and ABS related questions

Question	Response type	Accepted correct answers
How old are you?	15 / 16 / 17 / 18 / 19 / 20 / 21	-
What is your gender?	Male / Female / Other / Do not want to respond	-
Do you have a driver's permit or license?	Yes / No	-
- If yes, do you have a: permit, restricted, license	Permit / Restricted / License	-
Did you take or are taking driver's education at your high school or going to a driving school?	Yes – took driver's education / Yes – taking driver's education / No	-
What does ABS stand for?	Open-ended	Anti-lock braking system
If you had to describe the purpose of ABS to someone else, what would you say?	Open-ended	Keep the brakes from locking up, prevents skidding, keep control during hard braking
Have you ever used ABS?	Yes / No / I don't know	-
When learning to drive, did you ever practice using ABS?	Open-ended	-

6.2.3 Procedure

Participants were recruited during class by the researcher at the beginning of the school year. Interested students were given packets containing the consent, assent as well as copies of each document inside an envelope. The packets were returned to the respective teachers in order to gain extra credit and then were collected by the researcher. The survey took place during the beginning of the school year (September), either at the beginning or end of a class period. Participants used class laptops to access the test link through Qualtrics, which is an IRB approved survey tool.

6.2.4 Data Analysis

For the questions that had multiple choice or yes / no response types, a tally of correct or incorrect responses was counted. For the open-ended questions, a grading technique was used. One researcher went through each response for a question and determined if the answer was correct, incorrect or left blank. Separately, a high school science teacher completed the same process independently. It was not only important to have a second rater, but more importantly to have an expert with extensive experience grading high school level assignments. Ratings from the researcher and teacher for each question were reviewed for comparison; any differences in ratings between the researcher and teacher were discussed until a consensus was obtained.

The percentage of correct (or yes) responses was calculated for each question. The wrong, "I don't know", and blank responses were all counted as incorrect (or as a no). The percentage of correct (or yes) responses was compared between participants with a license/restricted license to those with a permit as well as those who had taken versus those who had not taken drivers education.

Independent sample t-tests were performed to determine if there were any differences in question responses between participants who had taken driver's education and those who had not taken driver's education.

6.3 Results

When participants were asked what ABS stands for, the only correct response accepted was anti-lock braking system. Only 21.7% of the students got the correct response, where some of the common incorrect responses were automatic braking system and assistive brake system. When asked to describe the purpose of ABS, the correct responses needed to include a statement about the prevention of wheel lock up during hard braking. Only 23.3% of participants correctly described the purpose. Only 33.3% of the participants reported using ABS. When asked if they ever practiced using ABS when they were learning to drive, 15.0% reported practicing using ABS. These results are summarized in Table 17 below.

Table 17. ABS knowledge and experience question results

Question		Mean	N
What does ABS stand for?	**Correct**	**21.7%**	13
	Incorrect	**78.3%**	47
	Mean difference (Correct-Incorrect)	-56.6%	
If you had to describe the purpose of ABS to someone else, what would you say?	**Correct**	**23.3%**	14
	Incorrect	**76.7%**	46
	Mean difference (Correct-Incorrect)	-53.4%	
Have you ever used ABS?	**Yes**	**33.3%**	20
	No	**66.7%**	40
	Mean difference (Yes-No)	-33.4%	
When learning to drive, did you ever practice using ABS?	**Yes**	**15.0%**	9
	No	**85.0%**	51
	Mean difference (Yes-No)	-70.0%	

6.3.1 Differences Between Participants Who Completed a Driver's Education Course and Participants Who Had Not

For drivers that completed a driver's education course, 24.3% correctly identified what ABS stands for and 21.6% correctly stated the purpose of ABS. Similarly, 17.4% of participants that did not take driver's education correctly identified what ABS stood for and 26.1% correctly stated the purpose of ABS. Participants who took driver's education had a higher percentage of participants that reported using ABS (37.8%) compared to those who did not take driver's education (26.1%, see Table 18). A similar trend was also observed for participants that practiced using ABS, where more participants who took driver's education reported practice using ABS (18.9%) than participants that did not take driver's education (8.7%). There were no statistically significant differences between students that had taken driver's education and those who had not on any of the questions.

Table 18. Comparison of ABS knowledge and experience questions between participants that had and had not taken a driver's education course

Question		Had driver's education (N=37)		No driver's education (N=23)		Mean difference (Had - no drivers ed.)
		Mean	N	Mean	N	
What does ABS stand for?	**Correct**	**24.3%**	9	**17.4%**	4	6.9%
	Incorrect	**75.7%**	28	**82.6%**	19	
	Mean difference (Correct-Incorrect)	-51.4%		-65.2%		
If you had to describe the purpose of ABS to someone else, what would you say?	**Correct**	**21.6%**	8	**26.1%**	6	-4.5%
	Incorrect	**78.4%**	29	**73.9%**	17	
	Mean difference (Correct-Incorrect)	-56.8%		-47.8%		
Have you ever used ABS?	**Yes**	**37.8%**	14	**26.1%**	6	11.7%
	No	**62.2%**	23	**73.9%**	17	

	Mean difference (Yes-No)	-24.4%		-47.8%		
When learning to drive, did you ever practice using ABS?	**Yes**	**18.9%**	7	**8.7%**	2	10.2%
	No	**81.1%**	30	**95.0%**	21	
	Mean difference (Yes-No)	-62.2%		-86.3%		

6.4 Discussion and Conclusion

The purpose of this survey was to understand if new drivers, especially those who had completed driver's education recently, have knowledge of and/or experience with ABS. Sixty high school students with licenses or restricted licenses participated in the survey, where 37 of the participants completed a driver's education course. The results of this study show that the majority (78.3%) of licensed high school participants did not understand what ABS stood for nor could the majority (76.7%) describe the purpose of ABS. Though many of the high school students had taken driver's education, there was not a meaningful difference between the students' knowledge when comparing the percentage of participants that knew what ABS stood for or the purpose of ABS between the participants that had completed and had not completed a driver's education course.

These findings are similar to Task 2 of NHTSA's Light Vehicle ABS Research Program, where a national phone survey was conducted to determine driver experience and expectations of ABS (Mazzae, Garrott, & Snyder). The national survey consisted of participants over the age of 16, where the largest age groups were between the ages of 30 to 60 and those over the age of 60. The results of the national phone survey showed that 38.8% of drivers knew what ABS stood for and 39.2% knew the advantages associated with ABS are prevention of wheel lockup and the resulting skidding (Mazzae, Garrott & Snyder, 2001).

There were no meaningful differences for the number of high school students who had used ABS or practiced using ABS between those who completed a driver's education course and those who had not for their experience using and practicing. The results of this study suggest that the majority of teen drivers, regardless of taking driver's education or not, do not have knowledge of and experience using ABS. This lack of knowledge of ABS could lead to potentially dangerous reactions from drivers, like release the brake pedal when ABS activates as a result of misunderstanding ABS feedback for a brake malfunction in emergency situations (Mazzae, Garrott, and Snyder, 2001). The results along with those from the previous studies suggest that the traditional instruction techniques may not be effective for teaching drivers about ABS.

CHAPTER SEVEN: STUDY V – INSTRUCTOR'S RATING OF DRIVER'S PERFORMANCE DURING AN ANTI-LOCK BRAKING EXERCISE ON A CLOSED-ROAD COURSE

The results of this study were published in Safety in September 2021 with the following citation: Mims, L., Brooks, J. O., Jenkins, T., Jenkins, C., Neczek, J., Isley, D., Bormann, A., Hayes., L. & Gubitosa, D. (2021). Instructor's Rating of Driver's Performance during an Anti-Lock Braking Exercise on a Closed-Road Course. *Safety*, *7*(3), 62.

7.1 Introduction

Traffic crashes are one of the primary causes of injuries and fatalities around the world (WHO, 2020). Most of today's crashes in the US can be attributed to driver error (94%), primarily consisting of recognition (41%), decision (33%) and performance errors (11%; Singh, 2018). As technology has advanced over time, the capabilities of vehicles have evolved over time. This shift has been observed in braking technology, where brakes not only serve to stop the vehicle, but also to assist the driver during emergency braking situations.

7.1.1 Anti-lock Braking System Overview

The anti-lock braking system (ABS) was developed to assist drivers during panic braking by preventing skidding or loss of control caused by locked wheels or a wheel that cannot rotate and is sliding (Duffy, 2009). When the wheels are locked, the driver does not retain control of the steering and thus cannot steer the vehicle even when turning the steering wheel. ABS was introduced on passenger vehicles in the 1980s with the hope of reducing the number of crashes (Kahane, 1994). Vehicles with conventional (pre-ABS) brakes required the driver to "pump" the brake pedal, or to rapidly press and release the brake pedal, during an emergency braking situation. Drivers often had a difficult time pumping the pedal at the correct frequency, which if performed incorrectly can cause the vehicle's wheels to lock and the driver to lose control of steering and braking of the vehicle. ABS automated this action for the driver by holding and releasing the brakes, which optimizes the brake pressure and prevents the wheels from locking and skidding. Since ABS quickly holds and releases the brake pressure, the driver experiences a vibration or "thumping" in the pedal when ABS is engaged. A benefit of ABS activation is the driver remains in control of the braking and can steer the vehicle (Kahane, 1994).

The National Highway Traffic Safety Administration (NHTSA) investigated crash records to see if there was a benefit of ABS. NHTSA's initial report showed that even though there was a reduction in fatal multi-vehicle crashes on wet roads, there was a significant increase in the number of fatal single vehicle run-off road crashes (Kahane, 1994). As a result of these findings, ABS was not required as standard safety equipment and NHTSA launched the Light Vehicle ABS Research Program to investigate why ABS was not effective in reducing all types of crashes (Garrott & Mazzae, 1999). The Light Vehicle ABS Research Program found that drivers did not understand the purpose of ABS, did not know when ABS was functioning, or if their vehicle was even equipped with ABS. Another major finding was that when ABS was activated, the vibration (thumping) feedback from the pedal was not understood by some drivers. This misunderstanding of the pedal vibration feedback could lead to dangerous reactions from drivers such as releasing the brake pedal (Mazzae, Garrott & Snyder, 2001). Though ABS began appearing on vehicles in the 1980s, it first appeared in the luxury vehicle segment before trickling down into the higher volume economy cars in the early 1990s. This initial evaluation of ABS examined traffic crashes between 1989 and 1993, which consisted of vehicles up to model year 1992 (Kahane, 1994). NHTSA conducted a second, multi-year observational study on ABS, spanning from 1995 to 2007 with a larger pool of vehicles equipped with ABS, where a similar trend of a decrease in multi-vehicle crashes on wet roads and an increase in run-off the road crashes was observed (Kahane & Dang, 2009).

In 2012, the functionality of ABS became standard safety equipment on all new passenger vehicles in the US as part of the Electronic Stability Control (ESC) system (NHTSA, 2007), due to ESC's reduction in crashes, especially those involving light trucks and SUVs (Kahane, 2014; Sivinski, 2011; Webb, 2017). ESC was created to help prevent loss of traction resulting in rotation caused by steering input that ABS cannot eliminate. Like ABS, ESC automatically makes braking adjustments at the individual wheels, but ESC also reduces engine output by comparing inputs from the driver (steering wheel angle) with the vehicle's motion (speed of the individual wheel, yaw rate and lateral acceleration; Dang, 2004). ESC has been estimated to reduce fatal rollovers by approximately 59.5% in cars and 74.0% in light trucks and SUVs as well as reducing other fatal single vehicle crashes by approximately 31.3% in cars and 45.5% in light trucks and SUVs (Kahane, 2014).

Though there have been improvements in vehicle technology and safety systems from an engineering perspective, a disproportionately high number of rear-end crashes still exist. In 2015, there were over two million rear-end collisions in the US, which account for 33.4% of all crashes, 6.8% of all fatal crashes, 32.4% of all injury causing crashes and 33.9% of crashes that resulted in property damage only (NHTSA, 2017b). In 2017, 39% of all fatal crashes in the US involved collisions with other vehicles, where 7.2% of all fatal crashes were rear-end crashes (NHTSA, 2019b). Even though ABS is required on vehicles and there is a high number of rear-end crashes in the US, ABS activation is not required during the license test to obtain a driver's license in the US (e.g., Florida Department of Highway Safety and Motor Vehicles, 2018; Georgia Department of Driver Services, 2018; State of California Department of Motor Vehicles, 2017; Texas Department of Public Service, 2017). Some states may ask drivers to stop quickly (e.g., Florida Department of Highway Safety and Motor Vehicles, 2018; Georgia Department of Driver Services, 2018; Texas Department of Public Service, 2017), but there is no specification for an ABS stop.

Few researchers have investigated the effects of ABS training on braking performance. Mollenhauer, Dingus, Carney, Hankey and Jahns (1997), investigated a low-cost training method involving drivers who had no previous experience with ABS. The drivers were divided into two groups, where one group of drivers was shown a pamphlet explaining the correct brake activation technique and the other was not. All participants drove on an icy track where they were asked to stop as quickly as possible. The results of the study showed that the drivers that reviewed the pamphlet used the correct activation technique and stopped an average of 35 ft sooner when traveling in a straight line compared to participants that did not review the pamphlet. The study included curved and surprise braking events, but there were no differences observed between the groups on either. Petersen, Barrett and Morrison (2006) investigated brake performance as a result of a two-day post-license training program. One group of drivers was enrolled in the program and the other group, a control group, received no training. The group enrolled in the program received ABS training using a two-phase braking technique, which was taught because it could be used in vehicles with and without ABS. The two-phase braking technique required the driver to first depress the pedal quickly near the maximum travel of the pedal, then, for the remaining distance of pedal travel, the driver applies pressure steadily until the pedal is fully depressed. The results showed that the group enrolled in the program did not rely on ABS as much as the control group to stop; therefore, the program group had smoother braking profiles. As a result, the program group took a full car length distance more to stop than the control group.

In order to provide ABS training and other defensive driving skills in the hopes of reducing driver error in controlled environments, post-license driving programs have emerged in the US. The programs vary drastically, from some that cater to new drivers with little experience, take place in parking lots, and are taught by volunteers who are driving enthusiasts to courses that cater to performance driving on closed road courses for individuals with racing experience. Regardless of the platform, the common goal between all programs is the desire to improve drivers' ability to control the vehicle using behind-the-wheel instruction in a controlled environment. Many of these programs include ABS exercises, with the goal of giving students the opportunity to activate ABS (e.g., https://www.guardyourlifechallenge.com/, https://putonthebrakes.org/, http://raceschool.com/, https://bondurant.com/). Even though multiple programs are available, there is limited data on the impact of these courses on drivers' knowledge of ABS as well as their ability to activate ABS.

7.1.2 Performance Driving Center Classes

The performance center collaborated with the research team to study driver ABS skills in a facility housing classrooms and a closed-road course (https://bmwperformancecenter.com). The center offers multiple classes for all driver's ages and skill levels, ranging from novice to advanced drivers. Some of the most popular courses are the teen and adult car control classes, which provide both classroom and behind-the-wheel instruction focused on defensive driving skills using a variety of exercises on the closed-road course These classes are either one or two full days. Drivers enrolled in these classes gain knowledge on proper driving behaviors, such as where and how far ahead to look when driving, optimal seating, as well as proper feet and hand positioning. Other goals of these classes are an improved understanding of vehicle safety systems like ABS and ESC, as well as experience performing emergency maneuvers including skid recovery and emergency lane changes. For additional details about the class, please see Mims et al. (2020c).

One key aspect of both the one and two-day classes is gaining hands-on experience using ABS. During the classroom instruction, the instructors provide an explanation of how ABS works, how to activate ABS and what drivers will experience while on the closed-road course during the ABS exercise. Drivers are instructed to slam on the brake pedal as hard as possible and hold the pedal until the vehicle comes to a complete stop. The instructors explain that due to the rapid engagement and release of the ABS system the drivers should expect to feel a vibration or “thumping” in the brake pedal. After the classroom portion, the participants move to the closed-road course for behind-the-wheel instruction (see Figure 26). There are typically a maximum of 16 individuals enrolled in a class. At the beginning of the class participants are divided into two groups, with a maximum of four vehicles per group. With up to two people per vehicle, the individuals are assigned to either drive first or be the passenger first.

Figure 26. Aerial view of the closed-road course (ABS exercise area in red).

Drivers slowly drive through the course and are instructed to brake at a designated set of cones and come to a complete stop before receiving feedback from the instructor. Participants are reminded to stomp on the brake pedal as quickly as possible and hold it all the way down until the vehicle came to a complete stop. As part of the instruction while driving through the course, the class participants stop near the cones and estimate the distance to stop at multiple speeds. The instructor then shows the actual distance needed to stop to help gain an understanding of how the distance needed to stop changes at different vehicle speeds.

Next, the drivers are instructed to accelerate to a given speed then activate ABS when reaching a designated set of cones (see Figure 27). Drivers begin the ABS exercise driving 30-35 miles per hour and with each run continuously increase their speed up to 55-60 miles per hour (mph). The area of the closed-road course where the exercise occurs has a turn near the end (Figure 27). As the speed of each practice run increases, the distance it takes the driver to stop dramatically increases. Once the driver is traveling around 50 mph, the drivers have to steer while they are braking. Each driver typically has six to seven runs, with the speed increasing on each run to a maximum of 60 mph. After each run, the drivers receive feedback from the instructor standing on the side of the course via a two-way radio (the driver's radio is located in the driver's door storage area). Once the first group of drivers completes the exercise, the drivers and passengers switch seating positions, and the exercise is repeated.

Figure 27. Map of the ABS exercise.

A previous study investigated the drivers' views of the class, where a pre and post-test survey was conducted with several one-day teen and adult classes (Mims et al., 2020c). The results suggested that both the teens (N = 80) and adults (N = 177) identified ABS braking as one of the most important topics taught during the class. The teens and adults reported increased competence in their ability to stomp on the brakes to activate ABS and steer while braking. On average teens and adults reported not feeling competent (average score of 3.2 for the teens and 3.6 for the adults out of 6, where 6 was fully competent to perform without further training) before the class and reported feeling more competent (average score of 5.6 for the teens and 5.4 for the adults out of 6) in their ability to activate ABS directly after the class. In regard to their ability to steer and brake simultaneously, the teens and adults did not feel competent prior to the class (average score of 2.8 for the teens and 3.5 for the adults), but once again felt more competent directly after the class (average score of 5.5 for the teens and 5.3 for the adults). The adults had the opportunity to participate in a follow-up phone interview six months after the class; they reported that ABS braking was one of the most used skills on the road from the entire class and ABS braking was the most frequently used skill from the class to avoid a crash.

The results from the previous study (Mims et al., 2020c), suggested that both teen and adult drivers considered the information about ABS and the experience activating ABS to be of high importance, which supports the hypothesis that many drivers did not have prior knowledge or experience with ABS. This is consistent with the observations from Mazzae, Garrott & Snyder (2001), that drivers did not understand the purpose of ABS. This study investigates drivers' understanding and ability to activate ABS based on professional driving instructors' performance ratings.

7.2 Methods

7.2.1 Participants

Participants in this study were drivers enrolled in a one-day performance driving class at a local closed-road course facility. Ninety participants were enrolled in the study. Eleven participants were dropped due to either missing instructor ratings or survey data. Of the remaining 79 participants, drivers' ages ranged from 18 to 78 years (M = 45.4, SD = 14.1), including 61 males and 18 females. There were 12 participants between the ages of 18 to 29, 15 participants between the ages of 30 to 39, 18 participants between the ages of 40 to 49, 21 participants between the ages of 50 to 59, 10 participants between the ages of 60 to 69, and 3 participants between the ages of 70 to 78. Participants received a $25 VISA gift card in exchange for their participation.

7.2.2 Survey and Rating Scale

A pre-test survey assessed each participant's demographic information, knowledge of ABS and previous experience with ABS, see Table 1. A post-test survey consisted of questions targeted the participants' experience during the class (Table 19).

Table 19. Pre- and post-test survey questions. Items in parentheses are requirements to participate in the study and/or examples of correct responses.

Survey	Question	Response option
Pre-test	What is your age? (Must be a minimum of 18 years old)	Open-ended
	What is your gender?	Open-ended
	Do you have a US driver's license? (Must have a US or international driver's license)	Yes / No
	What does ABS stand for? (Correct response: anti-lock braking system)	Open-ended
	If you had to describe the purpose of ABS to someone else, what would you say? (Examples of correct responses: keeping the wheels from locking up, automatically pumping the pedal, retaining the ability to steer, etc.)	Open-ended
	What do you feel when ABS is activated? (Examples of correct responses: vibration of the vehicle or brake pedal, etc.)	Open-ended
	Have you ever used ABS?	Yes / No
	- If yes, what did you experience?	Open-ended
	- If yes, the first time this happened to you, what did you think was going on?	Open-ended
	- If yes, at that moment, did you immediately know what was happening?	Yes / No
	- If yes, describe the environment.	Open-ended
	Have you ever practiced using ABS?	Yes / No / I don't know
	Did you take driver's education when you were learning to drive?	Yes / No
	Have you taken any additional driver's training courses (excluding driver's education)?	Yes / No
	- If yes, did you get behind the wheel experience with ABS?	Yes / No
Post-test	What was the hardest part about the ABS exercise?	Open-ended
	Has today's class changed your understanding of what ABS is, how it works, or what the driver feels?	Yes / No
	- If yes, what do you know now that you did not know before?	Open-ended

To have the instructors quantify the participants' performance when attempting to activate ABS, a behaviorally anchored rating scale (BARS) was developed to measure performance (Ohland et al., 2012). The development of BARS relies on the involvement of subject matter experts, who provide behavior-based examples of varying levels of performance for a task. Three driving instructors that regularly lead the ABS exercise collaborated with the research team to develop this scale. The scale consists of five ratings, where a rating of 1 represents no ABS activation, 2 represents brief activation, 3 represents some activation, 4 represents activation throughout most of the stop, and 5 represents full ABS activation throughout the entire stop, see Table 20 for a detailed description of each rating which includes a description of the driver's actions as well as what the instructor would observe.

Table 20. Description of each rating including what action the driver took and what the vehicle does or what the instructor sees.

Rating	Level of activation	Driver action	Instructor sees / what the vehicle does
1	None	Does not press the brake pedal hard enough to lock the wheels, thus not activating ABS	No rise or dive of the nose, wheels are continuously rolling
2	Brief	Presses the brake pedal hard enough to lock the wheels and activate ABS *momentarily*, the pedal pressure is not consistent or enough to sustain ABS	The wheels momentarily lock, and ABS releases the wheels causing what appears to be a ratcheting effect, the nose of the vehicle is pointing downward briefly
3	Some (three common scenarios)	A. Slams on the brake pedal to activate ABS then releases the brake pedal's pressure, so ABS is no longer activated through the remainder of the stop	A. The nose of the vehicle dives down and the wheels show the ratcheting effect, as pedal pressure is released the nose of the vehicle slowly rises and the wheels no longer are ratcheting
		B. Eases onto pressing the brake pedal, but not initially pressing hard enough to activate ABS, steadily applies enough brake pedal pressure to eventually activate ABS and sustain ABS through the rest of the stop	B. The nose of the vehicle slowly moves down up to the point where ABS and the ratcheting effect of the wheels begin, until the vehicle comes to a stop
		C. Combination of both scenarios A. & B. where eases onto the brake pedal and releases the pedal at the end of the stop	Combination of both A. & B. with the gradual downward motion of the nose of the vehicle until the ratcheting effect begins and the nose of the vehicle begins to rise near the end of the stop because ABS is no longer activated therefore the

			ratcheting effect disappears before the driver comes to a complete stop
4	Most (two common scenarios)	A. Releases the pressure from the brake pedal at the *very end* of the stop	A. The nose of the vehicle slowly rises as the vehicle comes to a stop, ratcheting of the wheels stops
		B. Eases onto the brake pedal at the *very beginning* of the stop	B. The nose of the vehicle moves down at the beginning of the stop until ABS is activated, and the ratcheting of the wheels begins
5	Full	Slams on the brake pedal and holds the pressure on the brake pedal until the vehicle comes to a complete stop	The nose of the vehicle dives at the very beginning of the stop, the ratcheting (locking and releasing) of the wheels begins and continues until the vehicle comes to a complete stop, the nose of the vehicle jumps upward when the vehicle comes to a stop

7.2.3 Procedure

Participants were recruited by a researcher in the order they arrived at the facility before the class began. All subjects read the consent form and provided their written approval prior to participating in the study. The study was conducted in accordance with the Declaration of Helsinki, and the protocol was approved by the Ethics Committee at Clemson University (IRB2017-215). After providing consent, each participant was given a folder containing the pre-test survey and post-test survey, which was left at their table in the classroom throughout the day. Participants completed the pre-test survey before the class began. Once the pre-test was complete, participants returned the pre-test to their folder.

The beginning of the classroom portion of the class includes an introduction as well as group, vehicle and driver assignments. Individuals are assigned to a group as well as a specific car. Each car had up to two individuals, one person is assigned to drive first and the other to be a passenger first, before switching roles. Typically, there was a maximum of 16 drivers per class, so each group had up to four vehicles with eight individuals. During the driving portion of the class, participants were tracked by their group, car and driver number assigned during the classroom portion.

After the completion of the classroom and warm up driving exercise, one group performed the ABS exercise while the other group drove through a different exercise on another part of the course. The instructor communicated with the individuals in each group over two-way radios. The researchers and instructor each had two radios, one for communication with the drivers and one for communication between the instructor and researcher. While the instructor took the class through the exercise and demonstration of ABS at different speeds, the researchers positioned themselves in a vehicle off the closed-road course, but with an excellent view of the exercise.

After the instructions and demonstrations were complete, the instructor took their place near the stopping point, so they were able to see the driver. Drivers were instructed when to start the exercise and what speed to drive over the radio. The target speed for the driver to achieve was determined by the instructor and was the driver's goal to reach before braking. In some instances, the instructor was very systematic starting at 30 mph regardless of the experience level of the class members while in other instances the instructors adjusted the speed based upon the drivers' level of experience. For the first run, the instructor suggested 30, 35, 40 or 45 mph. Speeds increased as drivers completed more runs of the ABS exercise, starting at a minimum of 30 mph and increasing to a maximum of 60 mph. For the final run (run 7), the instructor suggested 55 or 60 mph. Once instructed, the driver sped up to the desired speed and then attempted to activate ABS by braking near the designated cones. Once the driver came to a stop, the instructor provided feedback over the radio to the driver then provided the rating to only the researcher. The driver never heard the ratings provided to the researcher. The instructor provided the driver's speed and their 1 to 5 rating using the research radio while the driver traveled back to the starting line. During pilot testing the most common instructor feedback: Press the brake harder or Press the brake as hard as you can; *Press the pedal and keep it pressed until the vehicle comes to a complete stop; Slam the pedal from the start instead of easing onto it; Look where you want the vehicle to go; and Begin braking at the cones*, not before them were entered onto the data sheet so they did not need to be typed each time. As the speed of the exercise increased, drivers needed to look in the direction of the path they intended to follow to steer in the correct direction. The instructors only communicated to the researchers if the driver was looking in the direction of the path, they intended to go by saying "yes" or "no". All drivers completed a minimum of six runs while the majority of drivers had seven runs. After all drivers finished their runs, the driver and passenger switched roles and started the exercise over. After that group of individuals had experienced the ABS exercise as both the driver and passenger, the groups switched places on the course, and the process was repeated with the new group of drivers and passengers.

After the driving portion of the day, the participants returned to the classroom for the conclusion of the class, where the participants completed the post-test survey. Each participant filled out the post-test stored in their folder and when complete, placed the post-test back in their individual folder. The folders were collected after the class concluded.

7.2.4 Data Organization and Analysis

Many of the survey questions were open-ended requiring sorting, then grouping similar responses together to form categories. For example, the response category of pulsating or vibration of the brake pedal/vehicle included responses like pulsating brake pedal, vibration in foot, and shuddering in the brake pedal. After the categorization for each question was complete, the number of responses were tallied.

For the closed-road course data, the drivers' performance was examined using the instructor's ratings for the ABS runs. Much of the analyses focused on the initial ABS run since a driver on a road would only have one chance to use ABS in an emergency situation. Exploratory t-tests were conducted using survey responses to group drivers to explore if ABS performance varied based upon previous knowledge or experience with ABS. To identify potential differences between the ABS runs, an analysis of variance was performed. This analysis would determine if the participants' performance changed as they practiced more and approximately how much practice was necessary.

7.3 Results

7.3.1 Overview of the Initial Run of the ABS Exercise

During the ABS exercise, the participants had multiple attempts to activate ABS by slamming on the brake pedal at various speeds. The first run of the ABS exercise (30-45mph) was the participants' initial attempt to activate ABS on the closed-road course. The instructor ratings for the initial ABS run ranged between a 1 (no ABS activation) to 5 (full ABS activation) with an average of 3.86 out of 5. First, the survey responses associated with knowledge of ABS and prior experience using ABS were investigated using independent sample t-tests to explore if participants who correctly answered a question, or responded with a yes, differ from participants who incorrectly answered or responded with a no, for the initial run of the ABS exercise, see Table 21. There were no meaningful differences on instructor ratings between the groups who did and did not previously use ABS, know what ABS stands for or even know the purpose of ABS. Instructor ratings were significantly higher when participants knew what ABS feels like when activated prior to the class with an average rating of 4.14 in comparison to a rating of 3.33 for those with no prior knowledge, $t(1,45.19)=2.02$, $p=0.05$, Cohen's $d=0.50$. Having additional driver training beyond driver's education ($M=4.43$) resulted in significantly higher instructor ratings than no additional training ($M=3.63$), ($t(1,55.64)=2.39$, $p<0.05$, $d=0.55$). The 9 participants who had behind-the-wheel experience as part of their additional training ($M=5.00$), had significantly higher ratings than the 12 individuals who did not receive behind-the-wheel training as part of their experience ($M=4$; $t(1, 11.00)=2.57$, $p<0.05$). The largest difference between the groups was observed between participants who reported previously practicing ABS ($M=4.85$) having significantly higher ratings than those who did not report prior practice ($M=3.43$; $t(1,63.44)=5.12$, $p<0.05$, $d=1.10$).

Table 21. Average instructor ratings from run one for all participants based on their knowledge of ABS and previous experience using ABS.

	Survey response											
	Yes			No								
	Mean instructor rating	SD	N	Mean instructor rating	SD	N	Mean difference (Yes – No)	t	df	p	Cohen' s d	Power
Did the participant previously use ABS?	3.98	1.59	62	3.38	1.67	16	0.60	1.35	76	0.18	0.37	0.26
Did the participant know what ABS stands for?	3.89	1.60	57	3.76	1.70	21	0.13	0.32	76	0.75	0.08	0.06
Did the participant know the purpose of ABS?	4.09	1.47	53	3.36	1.82	25	0.73	1.76	39.30	0.09	0.44	0.43

Did the participant know what ABS feels like when it is activated?*	4.14	1.47	51	3.33	1.78	27	0.81*	2.02	45.19	0.05	0.50	0.55
Did the participant have any additional driver's training?*	4.43	1.12	21	3.63	1.73	56	0.80*	2.39	55.64	0.02	0.55	0.56
- If yes, did that that training include ABS experience?*	5.00	0.00	9	4.00	1.35	12	1.00*	2.57	11.00	0.03	Er	0.58
Did the participant ever practice using ABS?*	4.85	0.61	26	3.43	1.72	47	1.42*	5.12	63.44	0.00	0.87	0.94

*Significant difference between the two groups ($p<0.05$).

A total of 48 participants received a rating of 5 on their first run, demonstrating a stop with full ABS activation (see Figure 28). Fourteen participants were given ratings of 1, indicating there was no ABS activation during their initial run. Six participants received a rating of 2 indicating only brief ABS activation, five participants received a rating of 3 indicating some ABS activation, and five participants received a rating of 4 indicating ABS activation throughout most of the stop.

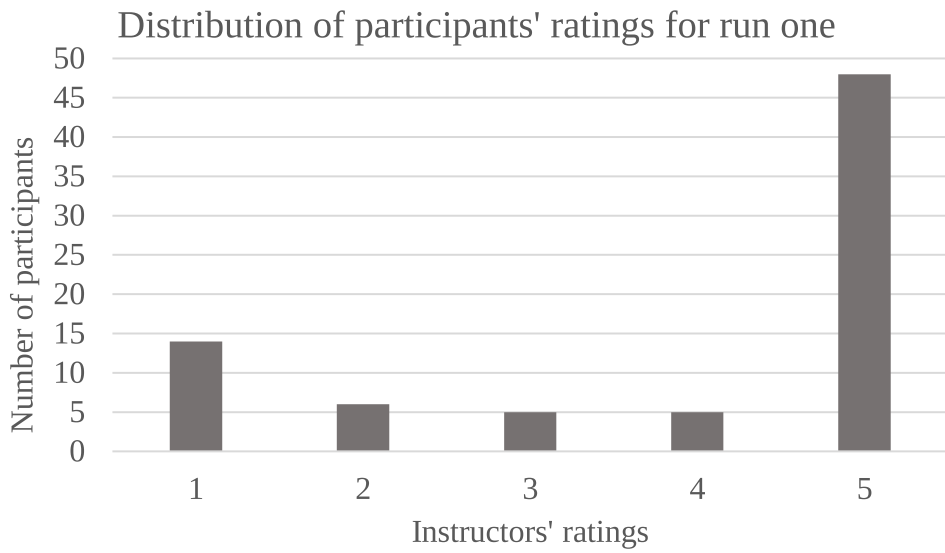


Figure 28. Number of participants that received each rating during the initial run where 1 is no ABS activation, 2 is brief ABS activation, 3 is some ABS activation, 4 is ABS activation throughout most of the stop, and 5 is full ABS activation throughout the entire stop.

As a result of the large number of individuals who received an instructor rating of 5 on the first run, for data analysis, participants were split into two groups to explore the survey responses, a "pass" group that included drivers who received an instructor rating of 5 or a "fail" group that included drivers who received a 1 through 4 instructor rating. The pass group included 48 participants while the fail group included 30 participants. Table 22 shows each item and the percentage of participants that fell within the pass or fail group. For example, gender is split into male and female, where 67.2% of the 61 males received an instructor rating of 5, or a pass, during the first run while 31.1% of the males received an instructor rating of 1 to 4 for the first run, thus falling into the fail group.

Table 22. Characteristics of participants that passed (instructor rating of 5) or failed (instructor rating of 1 through 4) during the first run of the ABS exercise.

		Pass	Fail	Difference (Pass – Fail)
	Number of participants (N=79)	48	30	18

Gender	Male (N=61)	67.2%	31.1%	36.1%
	Female (N=18)	38.9%	61.1%	-22.2%
State what ABS stands for. *Accepted response: anti-lock braking system*	Correct (N=56)	64.3%	37.5%	26.8%
	Incorrect (N=23)	52.2%	39.1%	13.0%
Describe the purpose of ABS. *Accepted responses: keeping the wheels from locking up, automatically pumping the pedal, retaining the ability to steer, etc.*	Correct (N=53)	66.7%	31.5%	35.2%
	Incorrect (N=23)	52.2%	47.8%	-4.4%
Describe what you feel when ABS is activated. *Accepted responses: vibration of the vehicle or brake pedal, etc.*	Correct (N=51)	70.6%	29.4%	41.2%
	Incorrect (N=28)	42.9%	53.6%	-10.7%
Previously used ABS	Yes (N=62)	67.7%	32.3%	35.5%
	No (N=17)	35.3%	58.8%	-23.5%
- If yes, what did you experience?	Pedal / vehicle vibration (N=34)	76.5%	23.5%	52.9%
	Braking in slick / slippery conditions (N=6)	66.6%	33.3%	33.3%
	Vehicle stopped (N=6)	66.6%	33.3%	33.3%
- If yes, the first time this happened to you, what did you think was going on?	ABS was activating (N=30)	66.6%	33.3%	33.3%
	Problem with the vehicle (N=8)	62.5%	37.5%	25.0%
	Brakes malfunctioning (N=7)	71.4%	28.6%	42.8%
- If yes, at that moment, did you immediately know what was happening?	Yes (N=40)	70.0%	30.0%	40.0%
	No (N=16)	68.8%	31.3%	37.5%
- If yes, describe the environment	Snow covered or icy road (N=16)	62.5%	37.5%	25.0%
	Wet road / raining (N=15)	60.0%	40.0%	20.0%
	Emergency stop was necessary (N=11)	54.6%	45.4%	9.0%
Previously practiced using ABS*	Yes (N=26)	92.3%	7.7%	84.6%
	No (N=47)	46.8%	53.2%	-6.4%
Any additional driver's training outside of driver's education	Yes (N=22)	72.7%	22.7%	50.0%
	No (N=56)	55.4%	44.6%	10.7%
- If yes, ABS experience part of the additional training**	Yes (N=11)	81.8%	0.0%	81.8%
	No (N=11)	63.6%	36.4%	27.2%

Experiencing the ABS exercise as a driver versus passenger first	Driver first (N=40)	55.0%	42.5%	12.5%
	Passenger first (N=39)	66.7%	33.3%	33.3%
Group order (first or second group to experience ABS exercise)	First (N=42)	71.4%	26.2%	45.2%
	Second (N=37)	48.6%	51.4%	-2.7%
What was the hardest part about the ABS exercise?	Maintaining pedal pressure until the vehicle stopped (N=18)	50.0%	50.0%	0.0%
	Pressing the pedal hard enough (N=15)	60.0%	40.0%	20.0%
	Looking where you want the vehicle to go (N=10)	60.0%	40.0%	20.0%
Has today's class changed your understanding of what ABS is, how it works, or what the driver feels?	Yes (N=46)	54.3%	43.5%	10.9%
	No (N=31)	67.7%	32.3%	35.5%
- If yes, what do you know now that you did not know before?	How ABS works (N=8)	50.0%	50.0%	0.0%
	How ABS feels when activated (N=6)	66.7%	33.3%	33.3%
	Ability to steer (N=6)	33.3%	66.7%	-33.3%

*Note: Six participants reported not knowing if they had previously practiced using ABS.
**Note: Data collection error where instructor rating was not recorded for two participants.

In comparison to drivers who failed their first ABS run (received an instructor rating of 1 through 4), the drivers who passed (received a rating of 5) had higher percentages for knowing what ABS stands for (64.3%), accurately describing the purpose of ABS (66.7%), and accurately describing what the driver feels when ABS is activated (70.6%). Those who passed the first run had more previous experience with ABS (67.7%) where most described experiencing pedal or vehicle vibration. Some of the greatest differentiators of those who passed versus those who did not pass were previous experience practicing ABS (92.3%), additional driver's training beyond driver's education (72.7%), and additional training that included ABS experience (81.8%). Participants described where and/or who they practiced with; the pass group answers consisted of post-license driving courses like the car control class (27.3%), in a parking lot (22.7%) or with family / friends (22.7%). Only two participants who reported practicing using ABS were in the fail group, where one participant described their practice as a car club class and the other participant practiced on their own and in driver's education. The research team was curious if observing the ABS exercise prior to driving or completing the ABS exercise or a different exercise would dramatically increase the pass rate of the latter opportunity, but neither case appeared to be dramatically more beneficial.

7.3.2 Overview of Runs One Through Seven

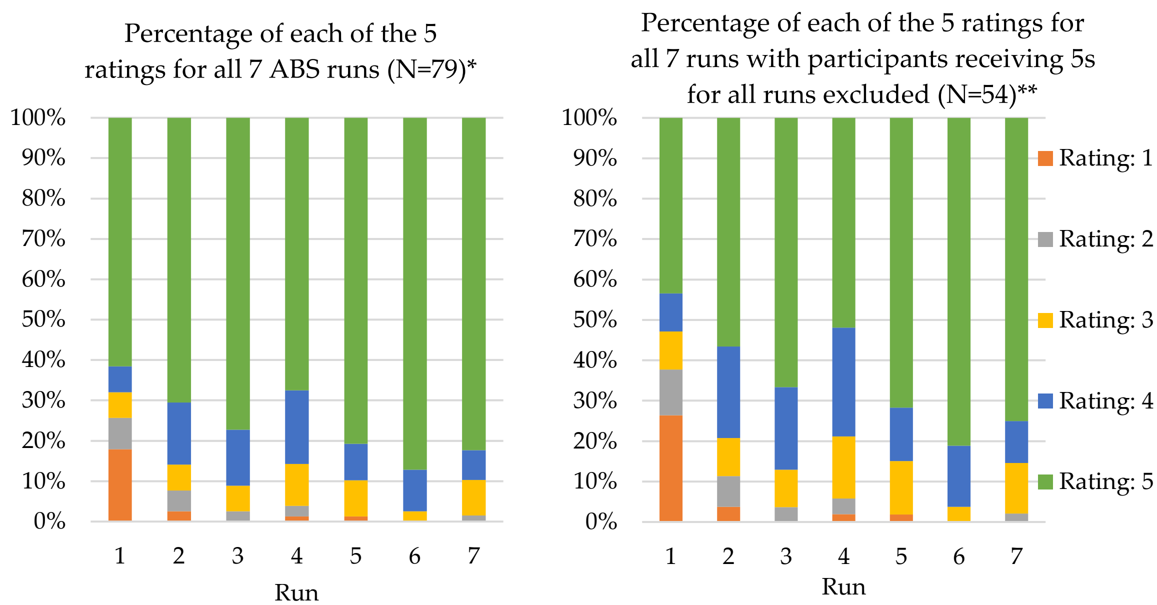
On run one, the instructors gave target speeds of 30, 35, 40 and 45 mph, with an average of 32.3 mph (SD= 5.2 mph). The majority of participants completed seven runs during the ABS exercise, see Table 23. To investigate if run number influenced ABS performance, a two-way analysis of variance was conducted. The results show that the run number had a significant impact on performance where ABS ratings increased with run number ($F(6, 529)=9.17$, $p<0.05$, $\eta p2=0.09$). Games-Howell post hoc comparisons were used because variance was not assumed. The average rating for run one (M=3.86) was significantly lower than runs three (M=4.66), five (M=4.68), six (M=4.85) and seven (M=4.71). The average ratings on run two (M=4.46) and run four (M=4.48) were significantly lower than run 6 (M=4.85).

Table 23. The target speed provided by the instructors (which varied between drivers, therefore the range, average speed, standard deviation (SD) are included as well as the instructors' average ABS rating and standard deviation. Since the sample size varied slightly for each run, the sample size is also included.

Run	Instructor suggested speed (mph)		Average speed (mph)	Speed SD	Average ABS instructor rating	ABS instructor rating SD	Sample size
	Min	Max					
1	30	45	32.3	5.24	3.86	1.62	78
2	40	50	41.0	2.45	4.46	1.00	78
3	40	50	45.7	2.08	4.66	0.71	79
4	45	55	50.1	1.26	4.48	0.88	77

5	45	60	54.6	2.29	4.67	0.82	78
6	50	60	58.7	2.46	4.85	0.43	78
7	55	60	59.8	0.87	4.71	0.69	68

Next, the distribution of the drivers' performance was explored by graphing the percentage of drivers who received each of the 5 possible ratings. First, the distribution of all 79 drivers is shown in Figure 29a with the percentage of 1 through 5 ratings that compose each of the seven runs. Since 25 drivers received an instructor rating of 5, demonstrating a stop with full ABS activation on all 7 runs, those 25 individuals' data were removed from Figure 4b which shows the same distribution of 1 through 5 ratings for all seven runs for the remaining 54 drivers. On Figure 29b, 56.6% of the participants received a 1-4 instructor rating (fail) on run one, 43.3% received a 1-4 rating on run two, 33.3% received a 1-4 rating on run three, 48.1% received a 1-4 rating on run four, 28.3% received a 1-4 rating on run five, 18.9% received a 1-4 rating on run six, and 25.0% received a 1-4 rating on run seven. On Figure 4b, run one had the largest percentage of instructor ratings of 1 and 2 in comparison to the other runs, with 26.4% and 11.3% of the drivers. Run four had the highest percentage of both 3 and 4 rating compared to the other runs with 15.4% and 26.9%, respectively.



(a) (b)

*Figure 29. (a) The percentage of 1-5 instructor ratings for the 7 runs for all 79 participant (b) The percentage of 1-5 instructor ratings for the runs without the 25 participants who received a perfect instructor rating of 5 for all runs in (a), *Runs 1-6 fluctuated slightly between 77-79 participants due to data collection errors, run 7 had 68 participants due to time limitations. **Runs 1-6 fluctuated between 52-54 participants due to data collection errors, run 7 had 48 participants due to time limitations.*

There were 19 participants who received an instructor rating of 5 on all of the ratings except one run, 12 participants received all but two ratings of 5 on all runs, four participants received all but three ratings of 5 on all runs, 15 participants received all but four ratings of 5 on all runs, and three participants received all but five ratings of 5 on all runs. One participant never received a rating of 5.

While the majority of participants (48) were able to fully activate ABS during their first run, other participants needed multiple runs in order to improve their skill and receive an instructor rating of 5, see Figure 30. A total of 14 participants needed two runs, 8 participants needed three runs, five participants needed four runs, two needed five runs, one needed six runs and the final driver was unable to gain a rating of 5 within seven runs, this participant's maximum instructor rating was 4.

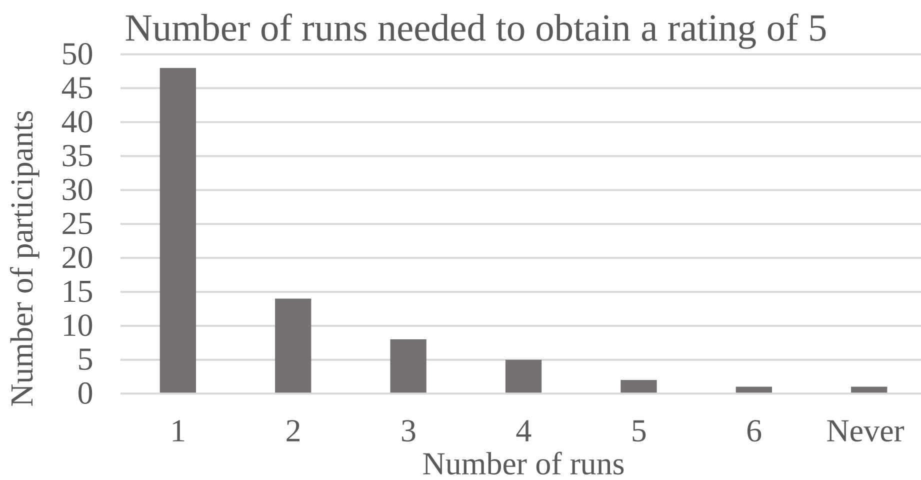


Figure 30. Number of runs needed to obtain an instructor rating of 5.

7.3.3 Instructor Feedback

During the exercise, drivers received feedback on their performance after each run. While all drivers received feedback after each run, only constructive comments were recorded. The feedback fell into five topical areas, the instructors provided each of the five comments from 56 to 27 times (the number of total times each type of feedback was given is in parentheses; see Table 24): *Press the pedal and keep it pressed until the vehicle comes to a complete stop* (56); *Look where you want the vehicle to go* (53); *Press the brake harder* or *Press the brake as hard as you can* (49); *Slam the pedal from the start* (of the stop) *instead of easing onto it* (31); and *Begin braking at the cones, not before them* (27). While the number of comments decreased as the number of runs increased, the type of feedback given to the participants also changed as the number of runs increased. Run one had the highest number of *Press the brake harder* or *Press the brake as hard as you can (21)* and *Begin braking at the cones, not before them (11)*. As the number of runs and speed increased (runs three through six), the feedback changed to include *Press the pedal and keep it pressed until the vehicle comes to a complete stop* (56) and *Look where you want the vehicle to go* (53).

Table 24. Feedback given to drivers during each run.

		Instructor suggested target speed (mph)		Avg. speed (mph)	Feedback					Comment count for each run
		Min	Max		Press the pedal and keep it pressed until the vehicle comes to a complete stop	Look where you want the vehicle to go	Press the brake harder or as hard as you can	Slam the pedal from the start instead of easing onto it	Begin braking at the cones, not before	
Run	1	30	45	32.3	4	1	**21**	9	**11**	46
	2	40	50	41.0	6	3	**10**	6	**5**	30
	3	40	50	45.7	**10**	10	6	7	1	34
	4	45	55	50.1	9	8	5	6	2	30
	5	45	60	54.6	**12**	**13**	3	0	3	31
	6	50	60	58.7	8	**11**	1	1	3	24
	7	55	60	59.8	7	7	3	2	2	21
	Count for each type of feedback				56	53	49	31	27	

7.4 Discussion

The goal of this study was to increase the body of literature regarding drivers' ability to activate ABS and determine if prior knowledge and/or experience impact drivers' performance activating ABS. Seventy-nine participants ranging in age from 18 to 78 years with an average age of 45, were recruited from car control classes that focused on defensive driving skills, with classroom and behind-the-wheel instruction on a closed-road course from professional driving instructors. Gaining knowledge and experience activating the anti-lock braking system (ABS) is one focus of the class. Based on a previous survey study (Mims et al., 2020c), having the opportunity to practice activating ABS on the closed-road course was reported as one of the most important and most used skills on the road after the class. To further explore drivers' understanding and ability to activate ABS, instructors rated drivers' ability to activate ABS on the closed-road course in addition to the participants completing of pre- and post-test surveys. The pre-test survey aimed to gain participants' knowledge of ABS as well as their previous experience activating ABS. During the behind-the-wheel instruction, ABS activation was rated by the instructors using a 1-5 behaviorally anchored rating scale focusing on the driver's ability to activate ABS, where a rating of 1 indicated no ABS activation and 5 indicated that ABS was fully activated throughout the entire stop. The post-test survey targeted participants change in understanding of ABS after the class. Since individuals enrolled in the car control classes are often enthusiasts of the BMW brand and/or driving, unlike the typical US driver, some of the participants enrolled in the car control class may have more driving experience and knowledge than the typical driver. The participant population had a broad age span and varying levels of prior experience with ABS, these characteristics are not observed in other studies (Mollenhauer et al., 1997; Petersen et al., 2006).

In a real-world driving scenario, a driver would only have one chance to activate ABS, therefore the results of the initial run of the ABS task were analyzed separately from all 7 runs. For the initial run, a total of 48 of the 79 participants (60.8%) received an instructor rating of 5, indicating full ABS activation during the entire stop. While it is unknown what percentage of the entire driving population can achieve full ABS activation during an emergency stop, it is likely this level of success (60.8%) is greater than the general driving population due to the participants who self-select to attend courses such as the car control classes. To better understand the attributes of the participants that were able to fully activate ABS on the first run, participants were divided into two groups, pass (instructor rating of 5) or fail (instructor rating of 1 to 4). Responses from the pre- and post-test survey responses were explored for both the pass and fail groups. The participants in the pass group had more experience with ABS, including 92.3% of participants reported previously practicing using ABS, 72.7% of participants had additional training outside of driver's education, and 67.7% of participants previously experienced ABS. For the participants in the pass group, 70.6% accurately described what the driver feels when ABS is activated, 66.7% correctly stated the purpose of ABS, and 64.3% correctly identified what ABS stands for. The combination of the instructor ratings plus the survey data, demonstrated that both previous knowledge of ABS and experience using ABS were associated with full ABS activation (instructor rating of 5) during the first run.

Next, regardless of performance on run one, participants who reported previous experience using ABS on their pre-test survey were asked follow-up questions. There were 49 participants that reported previously experiencing ABS prior to the class. Forty-two of the 49 participants who reported previous ABS experience, were in the pass group for run one. First, participants were asked what they experienced when ABS was activated. For those that reported experiencing pedal / vehicle vibration, 76.5% were members of the 42 pass group participants in the present study. When asked if they knew what was happening the first time they activated ABS, 68.7% of those who said no were members of the 42 pass group participants in the present study. Though many of the pass group participants with prior ABS experience reported knowing that ABS was activating the first time they experienced ABS, some of the participants in the 42 pass group thought there were issues with the vehicle or the brakes the first time they experienced ABS. The last follow-up question asked participants to describe the environment where they first experienced ABS. The most common responses were snow covered roads, icy roads, wet roads, or when an emergency stop was necessary. In many of these cases the likelihood of losing traction is increased due to the decrease in tire traction from the water, snow or ice on the road. A study conducted by Williams and Wells (1994), found that drivers who lived in colder climates with more snow and ice (Wisconsin, US) reported more experience with ABS than those who lived in areas with less snow and ice (North Carolina, US). Though ABS is more inclined to activate during emergency stops on slippery roads, it is unknown if some drivers think ABS only activates in slippery conditions. If drivers do not understand that ABS functions under all road conditions, they may not know to activate ABS in an emergency braking situation or be surprised when ABS is activated, which could cause panic in some drivers.

When looking at the average instructor rating for each of the seven runs for all participants, the three runs with the lowest average instructor ratings were run one (M=3.86), two (M=4.46) and four (M=4.48). The instructor's suggested speed ranged from 30 to 45mph (M=32.3) for run one and increased to 40 to 50mph (M=41.0) for run two. Though there was a progressive increase in speed from the first to second run, the overall average instructor rating improved by 0.6. While ABS performance steadily increased for the first three runs, performance on run four decreased (M=4.48). During the fourth run, the instructors increased the speed between 45 to 55mph (M=50.1). Steering input was needed in most runs when the speed was above 50mph, due to the curve at the end of the course where the ABS exercise took place. The fourth run was typically where participants began adding steering input while trying to activate ABS because of the increased stopping distance associated with higher speeds. The combination of steering input and ABS activation was difficult for some participants, which could be a factor in why the average instructor rating for the fourth run was lower than the third, and fifth through seventh runs. Performance activating ABS may be affected, or even decreased when steering input is required by the driver.

There were 25 participants who slammed on the brake pedal and held the pressure on the brake pedal until the vehicle came to a complete stop during each run and thus received instructor ratings of 5 for all runs. This was uncommon with the remaining 54 participants. Though the first run yielded 48 participants receiving an instructor rating of 5, 23 participants received at least one instructor rating of 1 through 4 in the remaining runs. The majority (54) of participants were not able to attain or sustain full activation of ABS during every run. As the number of runs increased, the average instructor rating increased (excluding run four), until run six with the highest average instructor rating (M=4.85). Some participants needed additional runs to fully activate ABS throughout the entire stop to receive an instructor rating of 5.

After each run, participants were given feedback by the instructors based on their performance activating ABS. For all participants on all runs collectively, the three most common types of feedback by the instructor were: *Press the pedal and keep it pressed until the vehicle comes to a complete stop; Look where you want the vehicle to go; and Press the brake harder or Press the brake as hard as you can.* This instructor feedback is consistent with what participants reported as the hardest parts of the ABS exercise, which included maintaining pedal pressure until the vehicle comes to a stop (N=18), pressing the pedal hard enough (N=15) and looking where you want the vehicle to go (N=10). Many of the participants had difficulty pressing the brake pedal hard enough, but also, once the pedal was pressed to maximum, sustaining the pressure to keep ABS activated throughout the entire stop.

When comparing the study discussed in this paper with other ABS training studies, there are some differences. The study examining the effectiveness of the low-cost training method using an informational pamphlet by Mollenhauer, Dingus, Carney, Hanley and Jahns (1997), showed that participants that reviewed the pamphlet stopped on average 35 ft sooner compared to the group of drivers that did not review the pamphlet when asked to stop as quickly as possible. In the Mollenhauer et al. (1997) study, participants were given a pamphlet to review, where the car control classes provide information in a classroom setting where participants are encouraged to ask questions. Another difference is the sample population; the age of participants in the Mollenhauer et al. (1997) study ranged from 20-26 with no prior ABS experience. In the current study, the average driver age is 45.5 and the range extends to drivers up to 78 years old. Some older drivers were taught to drive in vehicles without ABS, thus they may have different reactions to ABS than younger drivers. The Mollenhauer et al. (1997) study recruited participants that had no prior experience with ABS. Though there was a control group to see if the pamphlet made an impact on drivers who did not have prior experience with ABS, it is unknown how the pamphlet would affect drivers with prior ABS experience. The results of the current study showed that some of the participants reported that the first time they activated ABS they did not understand that ABS was activated, similar to the findings of NTHSA’s Light Vehicle Program that showed some drivers did not understand when ABS was being activated (Mazzae, Garrott & Snyder, 2001). Though some of the participants may have reported previously experiencing ABS, that experience did not equate to an accurate understanding or competency in performing a full ABS stop. The drivers that take car control classes at the performance center are enthusiasts, both for the BMW brand and for driving. The majority of the US population does not drive luxury or performance focused vehicles, nor are they driving enthusiasts. Though there was variation in knowledge and prior experience with ABS, 31.6% of participants demonstrated full activation of ABS over all runs, showing proficiency in their ability to activate ABS. Unlike other ABS studies, including the varying levels of knowledge and experience helped to better understand how prior knowledge and experience can influence performance activating ABS.

The Petersen et al. (2006) study compared a group of drivers that were enrolled in a two-day post-license driving program that received ABS training with a control group of drivers not enrolled in the program. Like the Mollenhauer et al. (1997) study, the Petersen et al. (2006) study consisted of younger drivers. The group that received the training group had an average age of 31.7 years and 14.2 average years of driving experience, and the control group had an average age of 27.9 and 9.2 average years of driving experience. It is unknown how the two-day post-license driving program would affect the performance of drivers with more driving experience. Another major difference between the Petersen et al. (2006) study and the current study, is the braking technique taught. The Petersen et al. (2006) study used a two-phase braking technique, where the driver depresses the pedal quickly until near maximum and then steadily applies pressure until the pedal is fully depressed. In the current study, participants are taught to press the brake pedal as hard as possible and hold the pedal in the fully depressed position until the vehicle comes to a complete stop. The results of the Petersen et al. (2006) study show longer stopping distances for drivers that had the two-phase training when compared to a control group. Since the two-phase technique requires drivers to steadily press the pedal as part of the second phase, this may cause the drivers to take longer distances to stop in comparison to a driver slamming and holding the brake. Further investigation is needed to see how the differences in technique affect stopping distance and ability to activate ABS.

The BMW performance center also hosts a non-profit event, the Guard Your Life Challenge (GYL), which is a half-day program offered to 30 teen (ages 15 to 18 years) drivers per class. The program focuses on ABS braking, skid recovery and distracted driving. In order to understand the views of the teen drivers a survey was completed by 134 volunteers directly after the program as well as a phone interview by 50 volunteers three months later. The results of the survey suggest that learning about ABS was one of the most important topics the teens learned about during the program, both directly after the program and three months later. The results of the phone interview suggest that participants avoided crashes and used the skills related to ABS braking within three months after the program (Mims et al., 2020b). Parents are required to stay for the classroom portion of the GYL program. As a result, a study was conducted with the parents to see if they benefitted from observing the program as well as their teens driving on the course (Mims et al., 2020a). A total of 134 parents completed the survey; the results showed that the majority of parents (85%) had previously experienced ABS, but only 16% of the parents described their participation in previous ABS training. Fifty-three percent of parents reported teaching their teen about ABS, where the majority (87%) had a discussion with their teen and only 13% used hands-on practice. Parents identified ABS braking as one of the most important topics that their teen learned as a result of the program, which is consistent with the teens' views. Seventy percent of parents reported that they would consider additional training for themselves after observing the teen program. The GYL program utilizes a subset of the classroom information on ABS and ABS exercise as the car control classes in the current study. Though the survey studies (Mims et al., 2020a; 2020b) do not provide ABS performance information, these studies surveyed a population of teens and parents enrolled in a half day driving program with essentially double the group size. Not many of the parents surveyed from the GYL program had been trained to activate ABS, nor did many use hands-on techniques to teach their teen about

ABS (Mims et al., 2020a). Knowledge and proper activation of ABS may not be known by typical teen and adult drivers.

Though there were some participants from the car control class that performed well, not all participants were able to fully activate ABS on every run. The group of drivers in the car control classes may have more prior driving experience and practice activating ABS than typical drivers, but some of the participants needed multiple runs to activate ABS. The typical driving population may or may not need additional runs than the group of participants in the car control class, particularly if they do not have prior knowledge and experience with ABS. The results of this study show the differences that knowledge and experience activating ABS have on a participants' ability to activate ABS. The more knowledge and increased experience a participant had with ABS, the higher the instructor rating typically was. One of the biggest differentiators was prior practice and training with ABS, where participants who reported practicing using ABS before the class had an average instructor rating of 4.85 and those who had ABS experience during additional training had an average instructor rating of 5 during the first run. Though understanding ABS and experiencing it made differences in the participant's performance activating ABS, intentional practice or training was a major factor in participants' gaining instructor ratings of 5 on the first run. Interestingly, the results yielded no significant difference in average instructor ratings between participants that were the driver versus the passenger first during the exercise, even though 66.7% of pass group participants were passengers first. This may indicate that observation may not be an effective learning method. Drivers may require behind-the-wheel practice or training to fully activate ABS in scenarios where it is necessary; this is consistent with previous NHTSA research that encouraged drivers to practice activating

ABS under varying conditions (Forkenbrock, Flick & Garrott, 1999), suggesting the need for behind-the-wheel practice, where the drive is actively trying to use ABS.

The action of braking involves perceiving a need to stop and the lagging action of moving the foot to the brake pedal. In previous research, time to perceive and act has been studied by drivers in vehicles as well as through models (Koppa, 1997). These studies and models rely on the presentation of a stimulus that the user must perceive and make the appropriate action (Brooks et al., 2016; 2017), which is consistent with an emergency braking scenario. During the ABS exercise in this study, drivers are actively attempting to activate ABS, so the cones that indicated the braking point are visible throughout the exercise. The driver estimates where to initiate the braking action based on the distance they are from the cones. The driver's perception-response time during the ABS exercise may not be consistent with previous studies or models that depend on the presentation of a stimulus.

7.5 Study Limitations

Due to the unique population that paid to enroll in the driving classes, the results may be skewed towards evaluating driving enthusiasts or luxury vehicle owner's performance activating ABS. Performance ratings data during the ABS exercise were collected from three different instructors. Some of the instructors were systematic, providing participants the same number of runs at specific suggested speeds while other instructors varied the number of runs and suggested speed based on the classes' level of experience and individual performance activating ABS.

7.6 Conclusions

The overarching goal of this study was to quantify performance activating ABS with participants' previous knowledge of and experience with ABS. Participants' performance was rated by the professional driving instructors using a behaviorally anchored rating scale, where a rating of 1 corresponded with no ABS activation and a 5 indicated full ABS activation throughout the stop. The results of the study showed that 60% of the participants were able to fully activate ABS during their first of several runs. Participants who self-reported to have prior training (5.00) or practice (4.85) using ABS had significantly higher performance activating ABS their first run, compared to those without previous practice or training. Not all participants were able to activate ABS during their first run, but the majority were successful at least once during the seven runs. For the participants who were not able to fully activate ABS, the most common feedback provided by the driving instructors was to maintain pedal pressure through the entire stop (56), look where you want the vehicle to go (53) and to press the brake pedal harder (49). Since the drivers with prior practice or training had the best performance activating ABS, especially during the initial runs, the results suggest that practice or training may be beneficial. Further investigation should explore different practice methods and the amount of practice necessary to use ABS in an emergency situation.

7.7 Future Research

Future studies should explore differences in performance between various methods of practice with ABS in order to better understand what type of practice drivers need to activate ABS in an emergency situation. Further investigations should include comparing individuals that practice activating ABS on their own versus those who had completed formal training. Future research should explore objective methods to quantify braking performance to allow for greater understanding of the braking behaviors to better understand performance deficiencies associated with varying methods of practice. These measures could include parameters like perception-response time, pedal force and/or stopping distance. Future research should assess participants' perception of their ability to activate ABS prior to receiving feedback from the driving instructor to understand the participants perception of their own performance in comparison to their actual performance. Many of the participants reported experiencing ABS in a slippery environment, future efforts should investigate participants' understanding of ABS in a variety of environments to explore if participants think ABS only activates in certain environmental conditions like snow. With the rapid changes in technology in vehicles surrounding user interfaces, future research should aim to investigate how these interfaces could provide guided practice for drivers for various safety features like ABS.

7.8 Practical Applications

The results of this study suggest that adults with prior practice or training with ABS are more likely to activate ABS during the first time attempting to activate it, which may also suggest that practice and/or training is necessary to for drivers fully activate ABS in the future. The results of this study were published in Safety as a journal article in September 2021 with the following citation: Mims, L., Brooks, J. O., Jenkins, T., Jenkins, C., Neczek, J., Isley, D., Bormann, A., Hayes., L. & Gubitosa, D. (2021). Instructor's Rating of Driver's Performance during an Anti-Lock Braking Exercise on a Closed-Road Course. *Safety*, *7*(3), 62.

The results from the instructor's rating of driver's performance activating ABS, indicate that drivers with experience feeling ABS activate, practice and/or training with ABS performed better during the initial run. Chapter Seven aims to explore biological signals from the driver during the ABS exercise.

CHAPTER EIGHT: STUDY VI – VARIATIONS IN ELECTRODERMAL ACTIVITY WHILE USING THE ANTI-LOCK BRAKING SYSTEM ON A CLOSED ROAD COURSE

8.1 Introduction

8.1.1 Anti-Lock Braking System (ABS)

One feature that may be necessary for individuals' safety during threatening driving situations is the antilock braking system (ABS). ABS allows the driver to maintain control of a vehicle's steering during intense braking situations by preventing the wheels from locking (Aly et al., 2011). For ABS to work properly, drivers must know how to interact with the brake pedal and respond to feedback from the pedal (Collet et al., 2005). Research has shown that many drivers (up to 50% or more) do not know how or when to activate ABS (Lee-Gosselin et al., 2001). ABS has been required on new vehicles in the United States since 2012 (NHTSA, 2007). Most US driver's license on-road tests do not require drivers to activate ABS (e.g., Florida, 2018; Georgia, 2018; California, 2017; Texas, 2017). The lack of driver knowledge about proper activation and the use of ABS limits the interpretation of field studies on the topic. The previously mentioned studies examined how braking scenarios can influence EDA. No known studies have specifically focused on EDA during the use of ABS. ABS use may result in increased stress compared to previous braking scenarios because of its higher deceleration rate and the requirement for users to respond to brake pedal feedback.

8.1.2 Biometrics and Braking

Several studies have described the biometrics of drivers during braking scenarios. One of the most frequently reported biometric measurements is electrodermal activity (EDA). Collet et al. (2014) concluded that EDA can objectively demonstrate driver stress when braking at various speeds while driving on a test track. Collet et al. (2014) also found EDA directly increases with braking intensity and is highest during emergency braking situations produced by a falling obstacle. Musicant et al. (2018) observed that EDA was at a maximum during episodes of intense braking by asking drivers to come to an immediate stop while traveling at 60 km/hr on a closed track. Musicant et al. (2018) also determined that EDA, heart rate (HR), and heart rate variability (HRV) can all correlate with braking intensity, with the relationship between EDA and braking intensity being the clearest of the three.

EDA is a broad feature that represents the electrical activity on the surface of the skin (Braithwaite et at., 2013). EDA can quantify the activation of the sympathetic nervous system (SNS). The SNS is stimulated when humans experience stress, leading to increases in heart rate, cardiac conduction, sweat gland activity, and other physiologic parameters to prepare the body to respond to perceived danger. This relationship between SNS activation and EDA values is what allows EDA to serve as a measure of one's stress level (Critchley, 2002).

EDA is analyzed via two of its components: skin conductance level (SCL) and skin conductance response (SCR). SCL represents the long-term component of EDA, while SCR is a temporary measure. The SCL provides a baseline value for nervous system arousal, while the SCRs are sudden, momentary increases in EDA in response to a stimulus (Braithwaite et al., 2013).

8.1.3 Multiple Arousal Theory and EDA

EDA is typically measured on the non-dominant hand (Bouscein, 2012) however, recent research has found EDA values can differ significantly between the two sides of the body especially during anxiety-inducing scenarios. These differences led to the proposal of the Multiple Arousal Theory, which states that numerous excitation pathways in the brain may lead to different nervous system innervation between sides of the upper body during emotional situations. The authors present evidence from multiple case studies with individuals experiencing a variety of emotions including excitement, stress, and anxiety. All of these scenarios showed asymmetry between left and right EDA. The authors reported cases from environments such as amusement parks and workplaces, but they did not study individuals during intense driving situations (Picard et al., 2016).

8.1.4 Performance Driving Center Classes

During the class, drivers experience both classroom and behind-the-wheel instruction. Although drivers completed multiple exercises during the day, this study only focuses on the morning classroom instruction and the ABS portion of the track exercises.

During the classroom instruction, the instructors provide a description of all of the maneuvers that participants will practice on the track, including an ABS exercise. For the ABS exercise specifically, instructors provide an explanation of how ABS works, what drivers will experience during the exercise, and how to activate ABS. Classroom instruction lasts approximately 2 hours, with roughly 20 minutes of this time focused solely on ABS instruction. Then all participants move to the track for behind-the-wheel instruction (see Figure 31). Two individuals were assigned to each vehicle; one individual completed the activity while the other was the passenger.

Figure 31. Aerial view of the closed road track (ABS exercise in red)

The ABS exercise allows drivers to gain experience activating ABS in a controlled environment. Before the exercise begins, drivers slowly drive through the course and are instructed to brake at a designated set of cones to come to a complete stop before getting feedback from the instructor. As part of the instruction, the drivers watch the instructor activate ABS from multiple speeds to show how braking distances changes with speed.

Next, drivers accelerate to a given speed then come to a complete stop by activating ABS before reaching a given point (see Figure 32). Drivers begin the exercise going 30-35 miles per hour and with each attempt of practice continuously increase their speed up to 55-60 miles per hour. At higher speeds (50+ miles per hour), drivers began to add steering input due to the increased braking distance.

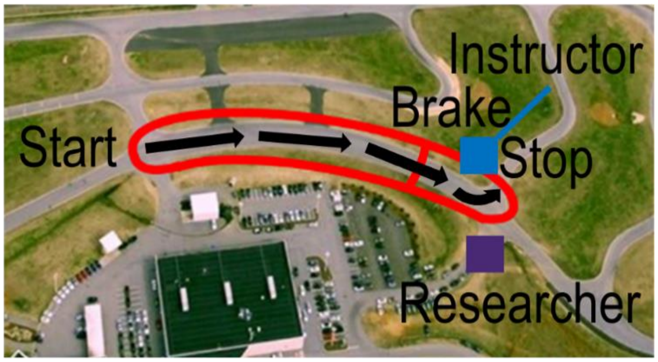


Figure 32. Closed road course and location of the ABS exercise (red)

Each driver had 6 to 7 attempts, with the speed increasing each time. After each attempt, the drivers receive feedback on their performance from the instructor nearby via two-way radio. Once the group completed the exercise, the drivers and passengers switched, and the exercise was repeated (see Table 25).

Table 25. Classroom and ABS components of the closed road course

Session	Description	Approximate duration
Classroom	Occurred indoors. Introduction to all of the track exercises- including the ABS exercise.	2 hours (20 min. on ABS instruction)
ABS instruction	Occurred on the track. All drivers received instructions for the ABS exercise as they drove through the course.	10 minutes
ABS driver	Drivers accelerated to a given speed and then used ABS to stop. This task was repeated 6 to 7 times per driver.	10-20 minutes
ABS passenger	Participants rode in the passenger seat while another driver performed the exercise.	10-20 minutes

8.2 Methods

8.2.1 Participants

Participants in this study were drivers enrolled in a one-day performance driving class at a local closed track facility. Participants included 17 drivers, ages 18 to 60 (M = 41.2, SD = 12.8), including 15 males and 2 females. Participants received a $25 VISA gift card in exchange for their participation.

8.2.2 Materials

Empatica E4 wearable devices (shown in Figure 3) recorded EDA data. This type of ambulatory measurement device was used because a non-invasive method was required. This device records heart rate, movement, skin temperature, and electrodermal activity (EDA). The

EDA data was recorded at four hertz via two 10mm silver coated electrodes (Empatica Incorporated, 2018).

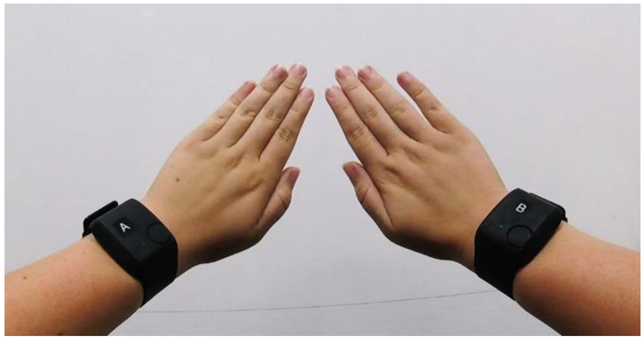


Figure 33. Two wearable devices worn by participants during the class

8.2.2 Procedure

8.2.2.1 Data Collection

Up to two participants per class were recruited. After providing consent, each participant was fitted with two Empatica E4 devices (one for each arm) that recorded biometric activity for the entire class. The devices were fitted using the manufacturer's recommended practice, but participants were allowed to adjust the fit of each device for their comfort if needed. The researchers manually recorded the time of all events in order to link the EDA data to the classroom and each component of the ABS exercise. During the ABS exercise, the researcher was located off the track in a parking lot with full view of the exercise (see Figure 32).

8.2.2.1 Data Analysis

After the data were collected and downloaded from each device, the EDA portions from the classroom and ABS related tasks (ABS instruction, ABS as a driver, and ABS as a passenger) were extracted from the full days' worth of data. In order to gain the skin conductance level (SCL) from the raw EDA data, a continuous decomposition analysis was performed using

Ledalab, a Matlab based software. The data were filtered using Ledalab's adaptive smoothing to remove any high frequency noise. Once the continuous decomposition analysis was complete, basic descriptive information could be viewed (Benedek & Kaernbach, 2010).

It is well known that individual biometric differences exist between participants, therefore the data were examined in multiple ways. When looking at the differences between the right and the left wrist's data for each participant, the percent difference between the wrists was calculated in order to normalize the data. A range correction from Dawson et al. (2001), also known as min-max normalization, was used to normalize the data to compare between participants. The range correction uses the minimum and maximum SCL values for each individual for comparison during the classroom and different parts of the ABS exercise. The data were also examined for outliers and were excluded if the values were greater than three times the standard deviation.

Two-way analysis of variance tests were conducted on the range corrected SCL data to determine if the wrist placement made a difference as well as if there were differences in SCL during the three different sections of the ABS exercise.

8.3 Results

In order to determine if there was a trend of one wrist providing higher SCL values than the other, the SCL of the right and left wrists were compared. Table 26 shows the percentage differences between the left and right wrists during the different parts of the class for each participant. There was a total of five participants whose SCL was consistently higher on the right wrist and four participants whose SCL was consistently higher on the left wrist. The eight remaining participants' SCL was mixed between the right and left wrist during the different parts of the class. When looking at the magnitude of the difference between the wrists, some participants show fairly consistent differences, while other participants do not. On average, the ABS driver portion of the class showed a higher difference between wrists, which could be due to the participant moving their hands to steer the vehicle during the ABS exercise.

Table 26 Percent difference in SCL between the right and left wrists during different parts of the class (shaded cells illustrate where the right was higher than the left).

Percent difference in SCL between the right and left wrists during different parts of the class				
Participants	**Classroom**	**ABS Instruction**	**ABS Driver**	**ABS Passenger**
	65.3%	76.7%	70.5%	69.0%
1	70.5%	64.7%	78.5%	69.3%
2	91.4%	86.8%	83.5%	94.3%
3	45.8%	89.4%	88.3%	62.0%
…	88.9%	35.2%	48.9%	36.9%
	15.7%	13.4%	322.4%	83.5%
	48.3%	28.4%	38.1%	42.8%
	13.9%	55.5%	32.1%	36.5%
	94.6%	18.5%	30.3%	13.8%
	32.0%	101.0%	911.8%*	31.1%
	6.2%	4.8%	24.2%	1.0%
	25.0%	56.1%	192.7%	183.7%
	15.4%	3.6%	58.4%	18.6%
	18.9%	4.0%	10.9%	55.7%
	22.0%	293.0%	44.7%	28.9%
	4.6%	17.2%	71.0%	28.4%
	48.7%	383.3%	394.4%	670.3%*
Average	41.2%	78.3%	99.3%	53.5%
Count:				
Right	7	9	11	8
Left	10	8	6	9

* Outliers excluded from average.
Note: Percentages were calculated as a percent different the left was from the right. The table shows the absolute value.

The results from the two-way ANOVA failed to reveal a significant difference (see Figure 34). There were no significant differences between the SCL values on the right and left wrists. When averaged across wrists, the ANOVA showed that there were no significant differences between the three different parts of the ABS exercise.

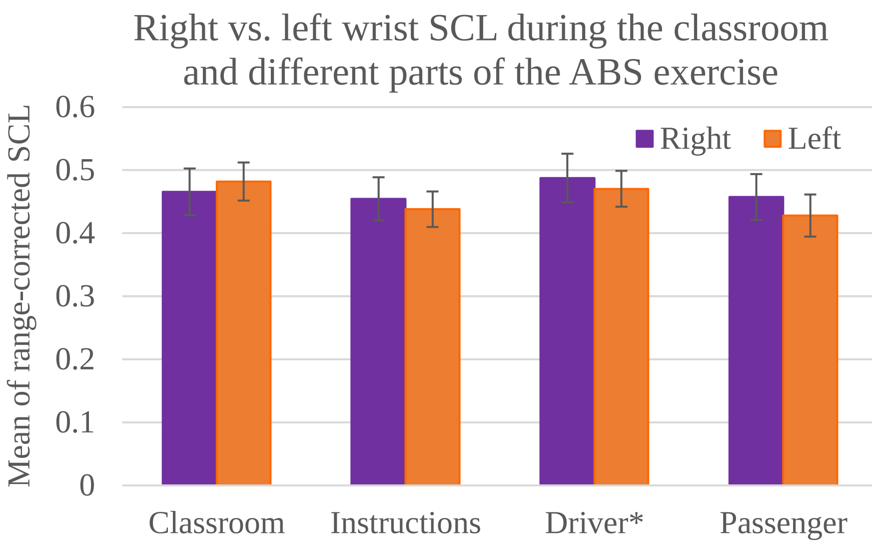


*Figure 34. Right vs. left wrist SCL during the classroom and different parts of the ABS exercise with standard error of the mean bars. *One participant's left wrist average SCL value during the ABS driver portion was considered an outlier and was excluded from this figure.*

8.4 Discussion

Seventeen individuals taking part in a local closed road course were fitted with Empatica E4 wearable devices on each wrist to record their electrodermal activity (EDA). The portions of the course when EDA was evaluated included the classroom instruction and anti-lock braking system (ABS) panic braking exercise, when the participant 1) received instruction, 2) as a driver and 3) as a passenger. There were no significant differences in EDA between the right and left wrists, thus there was no consistent evidence that one side of the body produced higher EDA values than the other. This may be due to the tremendous variability between participants. There were no significant differences between the classroom or the three ABS portions.

8.4.2 Multiple Arousal Theory

This research sought to explore if ABS braking supports the Multiple Arousal Theory. The authors of the Multiple Arousal theory cite case studies and lab-based studies that found asymmetry in the EDA of participants experiencing “anxiety, high-threat stakes, and seizures” among other intense situations, but none of their conditions investigated driving scenarios. (Picard et al., 2016).

Other research has discussed the presence of asymmetry in electrodermal activity. Bjørhei et al. (2019) exposed 25 participants to a series of stressful tasks while recording their EDA. They did not find any significant differences between the left and right sides, but eight individuals did show noticeable EDA asymmetry in portions of the experiment. Zontone et al. (2020) recorded the EDA of individuals as they drove through stressful environments in a driving simulator. The authors mentioned the chance of asymmetry, but they did not report any findings in relation to the Multiple Arousal Theory.

Since ABS activation typically occurs in panic braking situations, the Multiple Arousal Theory view would predict significant differences in SCL between wrists during the ABS exercise. Averaged across all participants, the SCL showed no trend distinct trend, and a larger sample size may be beneficial. Fifty-three percent of the participants had higher readings on one exclusive side of the body while others had mixed responses, supporting the asymmetry other researchers have previously observed (Bjørhei et al., 2019; Naveteur & Baqué, 1988). Further investigation into other influencing factors will be beneficial to determine if there is a link between those who had higher responses on the left, right or had a mix. These results suggest a possibility of asymmetry between wrists, and a larger sample size may once again provide to be beneficial.

8.4.3 Electrodermal Activity and Braking

Research has shown that the EDA of drivers is significantly higher when facing high-risk crash-avoidance situations (Ba et al., 2016) and when drivers are asked to come to a sudden stop compared to normal braking (Musicant et al., 2018). As a result, an increase in EDA was anticipated between the ABS instruction period, where participants were slowly driving through the course, and the ABS driver period.

8.5 Limitations

The majority of published studies on EDA and driving exercises have measured EDA using electrodes and gel placed on the fingers of the non-dominant hand, which is the recommended site for EDA recording (Bouscein et al., 2012). Due to the applied nature of this study, a less-invasive device to record participant's EDA was required. Therefore, measurements were taken from the wrist as opposed to the fingers. Additionally, electrodes on the fingers would have hindered the driver's ability to hold the steering wheel. Though ABS activation typically takes place in a panic situation, the exercise on the closed-road course did not involve surprise braking events; surprise events are anticipated to increase the likelihood of differences between the wrists.

The Empatica E4 prevented the examination of the skin conductance responses (SCRs) for short-term stimulus-related changes in the EDA. The sampling rate for the Empatica E4 device fell below the recommended rate for SCR analysis (Braithwaite et al. 2013). Since the individual ABS attempts lasted approximately 10 seconds, examining the SCRs may have yielded more significant changes.

8.6 Conclusions

Electrodermal activity (EDA) is used to study stress individuals experience in braking related driving scenarios. Traditionally, EDA is collected from the non-dominant wrist. The goal of this research was to explore the differences in EDA between the left and right wrists while activating the anti-lock braking system (ABS). The Multiple Arousal Theory, which states that multiple arousal pathways in the brain may lead to differing nervous system innervation to the different sides of the body during intense situations was tested. Drivers wore devices to record biometric data from both wrists. The day began with classroom instruction followed by driving on a closed-road track, where participants experienced ABS as a driver and passenger. Averaged across both wrists, the findings showed no differences between the classroom, ABS instruction, when driving or as a passenger during the ABS exercise. Overall, there was no consistent trend between wrists or any significant differences between them.

8.7 Implications for Future Research

The Empatica E4 prevented the examination of the skin conductance responses (SCRs) for short-term stimulus-related changes in the EDA. The sampling rate for the Empatica E4 device fell below the recommended rate for SCR analysis (Braithwaite et al. 2015). Since the individual ABS attempts lasted approximately 10 seconds, examining the SCRs may have yielded more significant changes. As technology continues to progress, it would be worthwhile to re-examine this question when easy to use devices with higher sampling rates become available.

8.8 Practical Applications

The results of this study conclude that the skin conductance response (SCR) measure of EDA is required for the short-term changes that may be associated with each ABS attempt. The

Empatica E4 cannot be used to measure SCR due to the limited sampling frequency. To measure SCR, increased sampling frequency is required, which involves a more invasive method of measurement not suitable for the participant population. For this reason, EDA measurement was not explored further.

CHAPTER NINE: STUDY VII – DEVELOPMENT OF AN EMERGENCY BRAKING PRACTICE EXERCISE WITH ANTI-LOCK BRAKING SYSTEM BRAKE PEDAL FEEDBACK ON A DRIVING SIMULATOR

9.1 Introduction

Rear-end crashes are one of the most common types of crashes in the U.S (NHTSA, 2017b; 2019b). To avoid or mitigate a rear-end crash, emergency braking strategies are necessary. During an emergency braking scenario, the anti-lock braking system (ABS) activates to prevent the wheels from locking up, which can cause loss of steering control and increase the stopping distance (Duffy, 2009). ABS quickly holds and releases the brakes to prevent the wheels from locking, which creates haptic feedback in the brake pedal (Duffy, 2009; Kahane, 1994). To activate ABS, the driver must slam the brake pedal to the maximum travel of the pedal and maintain pedal pressure until the vehicle comes to a complete stop. To help drivers increase performance during emergency braking while activating ABS, multiple researchers and government agencies have explored various methods of training.

9.1.1 ABS Training

There is limited research on methods for ABS training. Mollenhauer, Dingus, Carney, Hankey, and Jahns (1997) investigated the use of a low-cost training method that utilized a pamphlet that explained the correct ABS activation technique. Drivers ranging in age from 20 to 26 years of age with no previous ABS experience were divided into two groups, where 12 participants read the pamphlet and 15 control group participants did not read the pamphlet prior to completing braking tasks on a track. A track in Iowa was covered in a quarter inch of ice, where participants performed three different events requiring abrupt braking. First, straight line braking was examined at 25mph where participants were asked to stop the car as quickly as possible. Second, braking was evaluated while driving around a curve at 20mph. Last, a surprise event condition, where a Styrofoam block suddenly emerged into the driver's lane while exiting the track was evaluated. The results showed that all of the drivers who reviewed the pamphlet utilized the correct braking technique and stopped an average of 35 ft sooner than participants that had not reviewed the pamphlet in the straight-line braking event. There were no differences between the two groups during the curved braking or surprise braking events.

Petersen, Barrett, and Morrison (2006) 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, consisting of 13 participants, did not participate in the training 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 of the pedal, 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 50mph and 62mph on a track. The results concluded that the drivers who completed the program did not rely on ABS, thus had smoother braking profiles, but stopped an average of one car length longer than 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 include an overview of ABS and practice activating ABS. An example of a post-license advanced driver training class is the half day Guard Your Life Challenge (GYL) for teens and full day Car Control Classes for teens and adults, which both utilize the same track and some of the same exercises (Mims et al., 2020b; 2020c). During GYL and the Car Control Class, drivers practice activating ABS on a closed road track by speeding up to the instructor's suggested speed and slamming on the brakes at a set of designated cones. Drivers first run of the exercise is at approximately 30 mph and steadily with each subsequent run increase their speed while completing the braking exercise up to 60 mph, over approximately seven runs. After each run, drivers received feedback on their performance activating ABS from a professional driving instructor located near the stopping point via a two-way radio.

Mims et al., (2020b) investigated teen drivers' views of the Guard Your Life Challenge program, where teens experienced ABS braking, skid recovery, and the dangers of distracted driving. The program began with a classroom portion for teens and their parents to explain proper seating position, ABS, skid recovery, where to look while driving, etc., before the teens performed on-track exercises. One hundred and thirty-four teens completed a survey directly after the program and 50 teens participated in a follow-up phone interview three months after the program. The results from the survey directly after the class identified ABS as the third most important topic learned during the program. The results from the phone interview showed that 72% of the participants reported using the skills they learned from the program on the road and ABS was the most common skill used on the road (39%). Of the participants that reported using skills from the program on the road, 69% reported applying those skills to avoid a crash, with ABS being the most common skill used to avoid a crash (36%). The results of this study suggest that teens may benefit from practicing ABS activation.

A second study (Mims et al., 2020a) investigated parents' views of the Guard Your Life Challenge program. It was observed during the Mims et al., (2020b) study that parents were attentive during the classroom portion, and many observed the on-track portion. One hundred and thirty-four parents participated in a survey directly after the GYL program (Mims et al., 2020a). Parents were asked about their own experience with ABS, where 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 practice (Mims et al., 2020a). Though the majority of parents reported experiencing ABS, the lack of parents that provided hands-on practice for their teens suggests this is an area worthy of further investigation.

The Car Control Classes (CCC) offered to both teens and adults, are more involved than the half day Guard Your Life Challenge to include a full day of defensive driving with additional exercises, yet still include the ABS exercise. Teens and adults who completed the CCC were surveyed to understand their views of the CCC (Mims et al., 2020c). A total of 80 teens and 177 adults participated in a survey directly after the CCC and 64 adults participated in a follow-up phone interview six months later. The results of the survey showed that the adults identified ABS as the second most important topic learned, while the teens identified other exercises as being more important (skid recovery, where to look when driving, emergency lane change). During the phone interview, 77% of the adults reported using skills from the CCC on the road and 22% reported using ABS on the road since taking the course. Of adults that reported using skills from the CCC on the road, 23% reported using the skills from the CCC to avoid a crash, where 85% of those who used the skills to avoid a crash reported using ABS to avoid a crash. The results of the phone interview with the adults reflect the phone interview results from the teens in the Guard Your Life Challenge program (Mims et al., 2020b), where ABS was reported as a common skill used on the road and the most used skill reported to avoid a crash. The results of this study

(Mims et al., 2020c) suggest that many adults do not understand or have experience activating ABS prior to the CCC and may benefit from practice.

As a result of the research of the Guard Your Life Challenge program (Mims et al., 2020a; 2020b) and Car Control Class (Mims et al., 2020c) studies, the focus of the next study was narrowed to examine the ABS exercise exclusively. Mims et al., (2021) investigated how drivers' knowledge and experience with ABS prior to the CCC effected performance activating ABS during the on-track exercise. A total of 79 participants ranging from 18 to 78 years of age completed a survey prior to the class to gain the participants background knowledge of and experience activating ABS. During the ABS exercise, instructors rated participants' performance using a behaviorally anchored ratings scale. The scale was developed with the professional driving instructors and consisted of five ratings, where a rating of 1 corresponded to no ABS activation and a rating of 5 indicated full ABS activation during the entire stop (see Table 27).

Table 27. Behaviorally anchored rating scale to rate performance activating ABS

Rating	Level of activation	Driver action
1	**None**	Does not press the brake pedal hard enough to lock the wheels, thus not activating ABS
2	**Brief**	Presses the brake pedal hard enough to lock the wheels and activate ABS momentarily, the pedal pressure is not consistent or enough to sustain ABS
3	**Some (three common scenarios)**	A. Slams on the brake pedal to activate ABS then **releases the brake pedal's pressure**, so ABS is no longer activated through the remainder of the stop
		B. **Eases onto pressing the brake pedal**, but not initially pressing hard enough to activate ABS, steadily applies enough brake pedal pressure to eventually activate ABS and sustain ABS through the rest of the stop
		C. Combination of both scenarios A. & B. where eases onto the brake pedal and releases the pedal at the end of the stop
4	**Most (two common scenarios)**	A. **Releases the pressure from the brake pedal** at the very end of the stop
		B. **Eases onto the brake pedal** at the very beginning of the stop

5	**Full**	Slams on the brake pedal and holds the pressure on the brake pedal until the vehicle comes to a complete stop

The results of the study showed that the participants who had previous knowledge of what ABS felt like when it was activated, experienced additional driver's training (beyond driver's education) with and without ABS experience and 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 ABS exercise. During the exercise, all but one of the participants were able to receive a rating of 5, fully activating ABS at least once during their seven runs. The most common feedback 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%), and 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.

9.1.2 NHTSA Light Vehicle ABS Research Program

ABS became more common on passenger vehicles in the mid to late 1990s (Kahane & Dang, 2009), 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 was helping to reduce or mitigate crashes. During multiple investigations, ABS demonstrated benefits, like reductions in multiple vehicle crashes, but showed increases in single vehicle crashes involving a vehicle running off the road to lead in an impact with an object or rollover (Garrott & Mazzae, 1999). To investigate why there were increases in run off the road crashes with vehicles that were equipped with ABS, NHTSA created the Light Vehicle ABS Research Program. The ABS Research Program consisted of multiple research tasks to explore different hypotheses surrounding the increase in run off the road crashes. Three of the tasks within the ABS Research Program are related to driver training. Task 2 was a national phone survey with 3,508 participants about drivers' experience and expectations with ABS (Mazzae, Garrott & Snyder, 2001). Participants who had recently made a vehicle purchase (50% of the participants) were asked about their preferred method of education and practice with ABS at the dealer during their next vehicle purchase, assuming the vehicle had ABS. The options included required reading of the instructions for ABS and practice using it, listening to a 10-minute audiotape, watching a 10-minute video, practicing on a simulator for 15 minutes, 15 minutes of education and practice with ABS, or 30 minutes of education and practice with ABS. The most preferred options were a 10-minute video (33%) and 15 minutes of practice on a simulator (30%; Mazzae, Garrott & Snyder, 2001).

In Task 5.2/5.3, NHTSA explored the inclusion of a video on ABS operation and use (GM video for new vehicle buyers; https://www.youtube.com/watch?v=-YlZXdQlgrI) on collision avoidance behavior for 82 of the 246 total participants (Mazzae, Barickman, Forkenbrock & Baldwin, 2003). Participants drove on a closed road track through an intersection four times. During the fourth run, participants experienced a crash imminent scenario where a polystyrene vehicle representation encroached 6 feet into the participant's lane unexpectedly, causing the participant to make an emergency maneuver to attempt to avoid the vehicle representation. The results of this study showed no evidence that watching the video had any effect on crash avoidance behavior. Tasks 5.2/5.3 also explored the inclusion of braking practice before the crash imminent scenario. Some of the participants had a braking practice on the track with Jennite pad to simulate slippery conditions prior to the study scenario. Participants drove towards a cone in the center of the lane. The participant was told to avoid the cone while approaching it, but was not given any instructions on how to avoid the cone or how to activate ABS. The braking practice was intended to allow participants to experience ABS before the study scenario. Interestingly, the participants were not given instructions during the braking practice to activate ABS, nor was their performance during the practice reported, thus the participants may have not activated ABS. The results show that the braking practice did not have any effect on participant's crash avoidance behavior during the scenario (Mazzae et al., 2003).

NHTSA included the National Advanced Driving Simulator (NADS) in Task 5.1 (McGhee, 2000), which investigated crash avoidance behavior, like Task 5.2/5.3. NADS included a 190-degree forward and 60-degree rear field-of-view, with six-degrees-of-freedom base and fully instrumented cab (McGhee, 2000). NADS featured a 1993 Saturn SL2 cab but was retrofitted with ABS and utilized a full vehicle dynamics model from a Ford Taurus. The simulator was used to explore collision avoidance behaviors of drivers, rather than exploring ABS training.

NHTSA's research showed that an instructional video or practice in a simulator were the preferred methods of education and practice for gaining knowledge about ABS (Mazzae, Garrott & Snyder, 2001). The instructional video on ABS and braking practice were not shown to impact driver behavior (Mazzae et al., 2003). Although the NHTSA results suggest that practice on a driving simulator was a preferred method by participants, it was not explored.

9.1.3 Simulators for Driver Training

Simulators provide a safe environment to explore and practice driving behavior. They offer the ability to create a repeatable, controlled driving task or environment which is ideal for research and training purposes. Simulators have been used as a clinical assessment and rehabilitation tool for driving by occupational therapists (Touchinsky, Chew, Brooks, & Evans, 2018). Due to the repeatability of simulators compared to on-road studies, simulators have been shown to detect impairments and errors with at-risk drivers (Classen & Brooks, 2014). The U.S. Department of Veterans Affairs driver rehabilitation program utilizes driving simulators as an evaluation and training tool for adults returning to drive after injury or to help determine fitness (Neczek, Kelsch & Brooks, 2018). Simulators are also used to train new drivers, including at-risk driver populations including individuals with intellectual disabilities. New drivers can become overwhelmed when learning how to operate the steering wheel and pedals in the context of a naturalistic driving scene. Therefore, Brooks, Mossey, Tyler, and Collins (2013) suggest the use of scenarios that allow drivers to practice focusing on one aspect of driving, such a turning the steering wheel or operating the pedals, prior to scenarios with a roadway scene. Brooks et al. (2016) developed and explored the use of interactive exercises, where drivers focus on developing motor skills associated with driving without a driving scene. Rather, the interactive exercises consist of visual representation of a steering wheel, gas and brake pedals or a stoplight, instead of a roadway scene. Brooks et al. (2016) demonstrated that the interactive exercises were an effective training tool for both young neurotypical drivers as well as teens with intellectual disabilities. One issue with simulators that must be considered is simulator sickness, especially with roadway scenes that include turns and abrupt braking events (Brooks et al., 2010). Simulator sickness encompasses many factors, but one of the most prominent is visual immersion in simulators with large displays, and therefore larger field-of-views, where more immersive simulators increase the likelihood of simulator sickness (Brooks et al., 2016). A benefit of the interactive exercises is that simulator sickness is not possible.

9.1.4 Study Aims

This study explored ABS training using an interactive exercise on a driving simulator, where participants practice emergency braking while experiencing haptic brake pedal feedback similar to that associated with ABS activation. The simulator provided a safe, repeatable task to practice ABS braking without the need of a full vehicle or roadway and can provide immediate and consistent feedback on a driver's ability to activate ABS.

The purpose of this study was to determine if a new interactive exercise on a driving simulator could provide participants with the needed feedback to properly complete an emergency braking task engaging ABS. To answer this question, participants with and without prior knowledge of and experience with ABS participated in the study. Individuals with prior experience using ABS provided insight on the feel of the ABS feedback, where individuals without prior ABS experience provided true reactions to the ABS feedback. Mims et al. (2021) identified background factors that influenced participants' ability to activate ABS. Specifically, participants that understood the feel of ABS when activated, participated in additional driver's training beyond driver's education either with or without ABS experience, or those who practiced activating ABS had significantly higher performance activating ABS compared to other participants without the prior knowledge or experience (Mims et al., 2021).

Interestingly, participants that had previously experienced ABS did not perform significantly better than those that had not experienced ABS (Mims et al., 2021). Participants were asked about their knowledge of and experience with ABS prior to the car control class where they receive an overview of ABS. When participants were asked to describe what the driver feels when ABS is activated, the participants that did not understand what ABS was or mistook it for another component did not answer correctly. This may be why there was a significant difference in performance for those that understood what ABS feels like when activated versus those who reported previously experiencing ABS. For this reason, participants in the current study were grouped by their experience and understanding of the feel of ABS when it is activated.

First a usability study was completed to ensure the *Pedals Emergency Stop* © interactive exercise works as designed prior to the study.

9.2 Usability Study

9.2.1 Methods

9.2.1.1 Participants

Participants from the track study examining the driving instructor’s rating of ABS performance (Mims et al., 2021) ranged between 18 and 78 years of age with a means of 45.4 years. Due to the large age range from the Mims et al. (2021) study and the potential to have participants of a vast range of ages in future track studies, the only age requirement for this usability study was to be over the age of 18. Participants were required to have a driver’s license. The participants included 28 adults. Due to left foot braking, experimenter error and not passing the training exercises, four participants’ data were not included in the analysis. Of the remaining 24 participants, ages ranged between 21 and 54 years of age, with an average age of 26.8 (SD=6.7). Three participants were female and 21 were male. Participants were recruited from the university and surrounding community.

9.2.1.2 Simulator

The purpose of the simulator was to allow users to complete a task allowing for practice emergency braking and feel haptic feedback that is consistent with ABS activation and feedback in a vehicle. The simulator was integrated with a DriveSafety interactive exercise and software which was build using commercially available products that were assembled to enable the desired ABS feedback (see Figure 35). Descriptions of each element are discussed.

Figure 35. Simulator setup

9.2.1.2.1 Monitor

The interactive exercises were displayed on a single screen, a 34” LG Class 21:9 UltraWide Full HD IPS Gaming Monitor.

9.2.1.2.2 Pedals

For participants to practice emergency braking, a commercially available pedal set was used.

Prior to the selection of the pedal set, it was important to review the common characteristics of pedals in passenger vehicles. Pedals are categorized by the point at which the pedal arm rotates, or the fulcrum. Figure 36 depicts the two common types of pedals in current passenger vehicles, which are the pendulum (also called suspended; SAE, 2009) and organ (also called treadle; SAE, 2009).

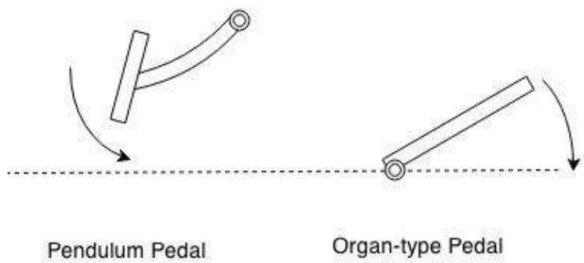


Figure 36. Pendulum and organ pedal types (Black, 1966)

Another prevalent characteristic of passenger vehicle pedals is the offset between the accelerator and brake pedal where the brake pedal is at a higher vertical position compared to the accelerator pedal (see Figure 37). This offset is intended to help drivers avoid pressing both pedals simultaneously (SAE, 2009),

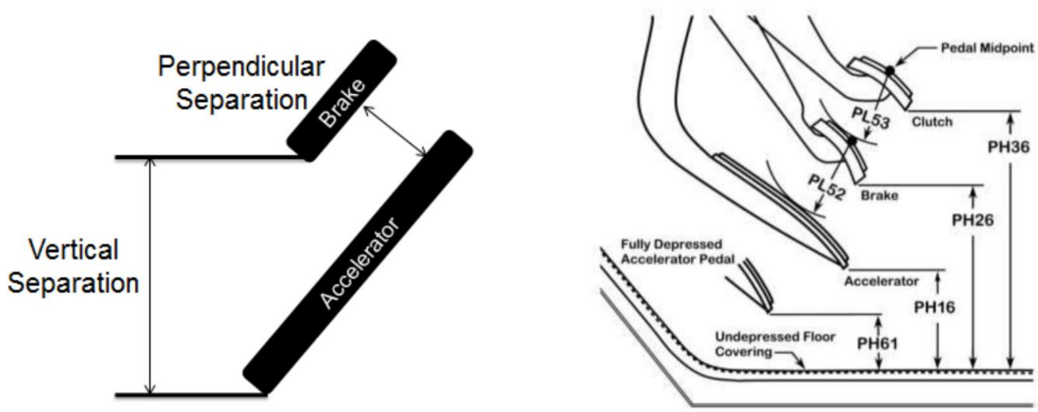


Figure 37. Off set or separation between the accelerator and brake pedals (left Xi, 2015; right SAE 2009)

After completing an inventory of the gaming market for pedal sets that had similar characteristics to passenger vehicles (Wessner et al., 2019), the Fanatec ClubSport V3 Inverted pedals were selected. This pedal set is one of few gaming pedal sets that offered a pendulum or suspended brake pedal along with an organ style accelerator pedal (see Figure 38).

Figure 38. Fanatec ClubSport V3 Inverted pedals (https://fanatec.com/us-en/pedals/clubsport-pedals-v3-inverted)

The Fanatec ClubSport V3 brake pedal has an adjustable damper to change the pedal resistance and adjustable load cell to change the pedal travel. For this study, the brake pedal's adjustable damper was set to zero to allow the pedal to move freely, if the damper was set above zero the brake pedal was very hard to press and moved too slowly. The damper setting was evaluated during a human factors course usability study on multiple off-the-shelf pedal sets with 30 participants (Gupta et al., 2019). The resistance of the pedal was verified by a subject matter expect. 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).

A unique feature of the Fanatec ClubSport V3 pedal set was vibratory feedback. Small motors mounted to the backside of both the accelerator and brake pedals created vibrations intended to simulate road noise, ABS activation and skidding during a driving game. Though the motors provide some feedback, the vibration was not intense enough to be consistent with the feedback generated by ABS in a vehicle, as a result, they were disabled.

In order for the Fanatec ClubSport V3 Inverted pedals to communicate with the simulator, a Fanatec wheelbase was needed. The wheelbase served as the computer to communicate information such as pedal position to the DriveSafety system. The Fanatec CSL Elite Wheelbase was selected to compliment the pedals, see Figure 39.

Figure 39. Fanatec CSL Elite Wheelbase (https://fanatec.com/us-en/racing-wheels-wheel-bases/wheel-bases/csl-elite-wheel-base#downloads)

9.2.1.2.3 ABS Haptic Brake Pedal Feedback

Since the vibration feedback motors on the Fanatec ClubSport V3 Inverted pedals were not intense enough, a different source of haptic feedback was required. The ButtKicker Gamer2 typically delivers haptic feedback to gamers by attaching the device to the base of an office chair (see Figure 40). The ButtKicker delivers adjustable vibration through an audio input.

Figure 40. ButtKicker Gamer2 (https://thebuttkicker.com/buttkicker-gamer2)

To simulate the brake pedal feedback associated with ABS activation, the ButtKicker Gamer2 was installed onto the Fanatec ClubSport V3 pedal assembly by tightening the clamping mechanism to the upper horizontal support for the brake pedal (see Figure 41). The ButtKicker was not attached directly to the brake pedal due to an interruption with the brake pedal signal caused by the force of the clamping mechanism when the ButtKicker was clamped onto the brake pedal's load cell.

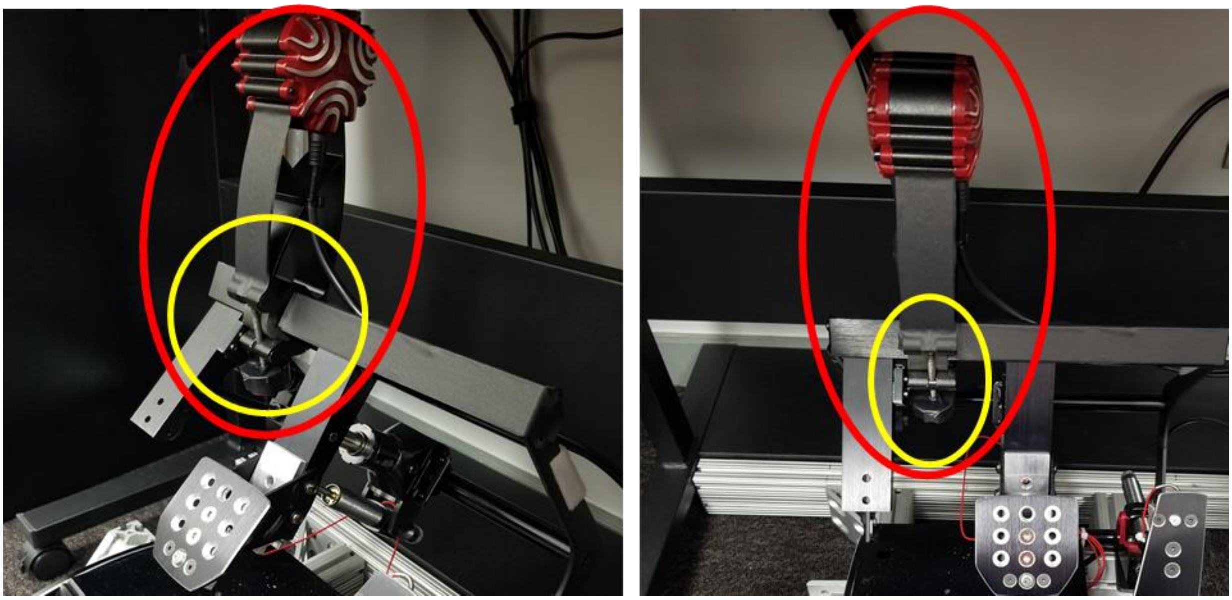


Figure 41. ButtKicker Gamer2 mounted to the pedal set. The red circle highlights the ButtKicker Gamer2, and the yellow circle highlights the attachment point.

To simulate feedback from ABS through the ButtKicker, an audio file containing the vibration (frequencies) associated with ABS activation in a vehicle was required. The frequency at which today's ABS operates varies by manufacturer and the values are not commonly published. To gain the frequency of the feedback the driver feels through the brake pedal, physical measurements were required.

9.2.1.2.3.1 Measurement of ABS Brake Pedal Feedback on a Vehicle

To measure ABS feedback from the brake pedal on a vehicle, two wireless Bluetooth accelerometers (WitMotion BTW901CL) wirelessly sent data to a Microsoft Surface. The first accelerometer was mounted to the backside of the brake pedal using 3M mounting tape (414LONGDC). The accelerometer mounted to the brake pedal captured the acceleration from the brake pedal and vehicle. The other accelerometer was mounted to the backside of the center console to capture the overall vehicle motion. The accelerometers sampled data at 100 Hz.

The test vehicle was a 2012 Toyota Camry LE. The vehicle was driven for 10 minutes with a minimum of five stops where ABS was activated before measurements were recorded to ensure the brakes were warm. Once the accelerometers began logging data, multiple test runs with ABS activation were made to collect the acceleration values from the brake pedal and the vehicle. Each test run began with the vehicle at a complete stop, then the vehicle accelerated until reaching 55mph, then the driver stomped on the brake pedal to activate ABS until the vehicle came to a complete stop.

The test speed of 55 mph was chosen due to the duration that ABS was be activated, to allow for sufficient data collection. In addition, most fatal single and multi-vehicle crashes occur at 55 mph (NHTSA, 2017b).

After the test runs were complete, the data were downloaded using the WitMotion software. The accelerometer data were recorded in an x, y, z format. The data from the test session was plotted to determine where the large changes in accelerometer values occurred, which indicated a test run. The data were then separated into individual test runs. Figure 42 shows the acceleration data from one test run for both the brake pedal and the vehicle.

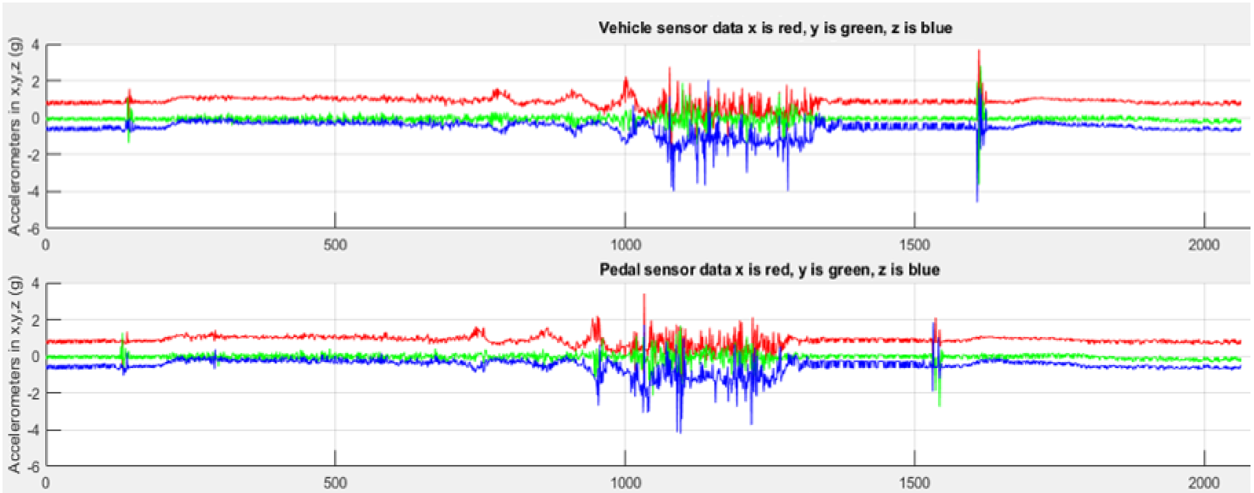


Figure 42. Accelerometer data where the x axis is red, y axis is green, and z axis is blue from the vehicle (top) and brake pedal (bottom) during a test run at 55mph in the 2012 Toyota Camry

The x, y, z accelerometer data were converted into a single acceleration value for the brake pedal and vehicle accelerations (Figure 43).

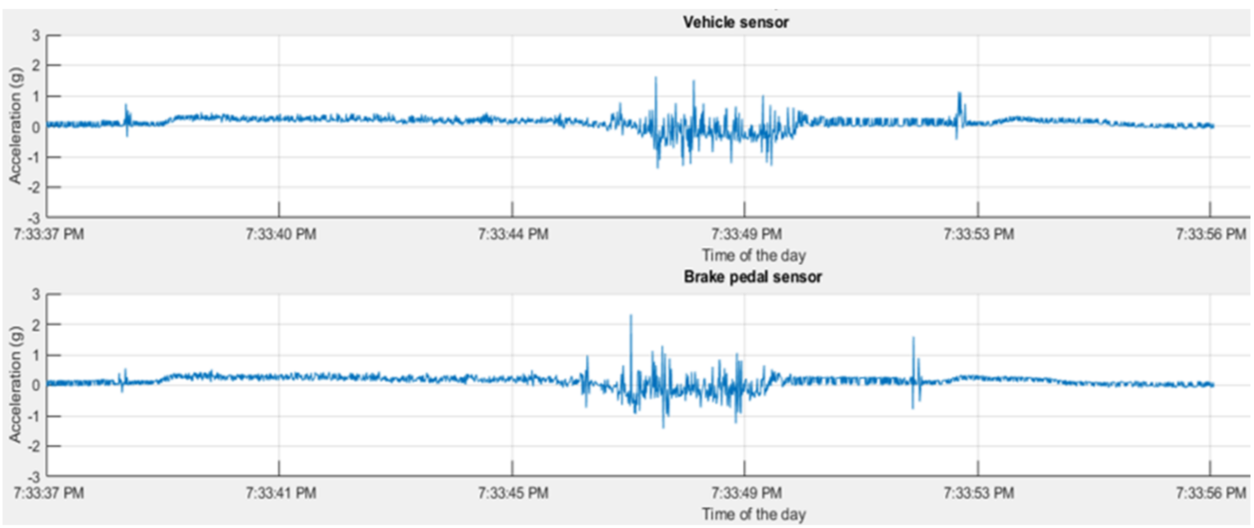


Figure 43. Single acceleration values for the vehicle (top) and brake pedal (bottom) during a test run at 55mph in the 2012 Toyota Camry

The brake pedal data were compared to the vehicle data to show that both signals were similar. The motion the vehicle experienced from ABS being activated was similar to that of the pedal. To verify that the signal from the brake pedal and vehicle were similar, the frequency components were evaluated for each signal using Audacity software. First, the data were scaled between -1 to 1 to be imported into the software, which changed the intensity but not the frequencies within the data. A Hamming window was selected to filter for noise. Figure 44 shows the frequency distribution when ABS was activated. The peaks represent the individual frequency components, which show that the frequencies the brake pedal experienced are below 40 Hz. The major frequency components were at approximately 7 Hz, 15 Hz, 22 Hz, 29 Hz, and 36 Hz.

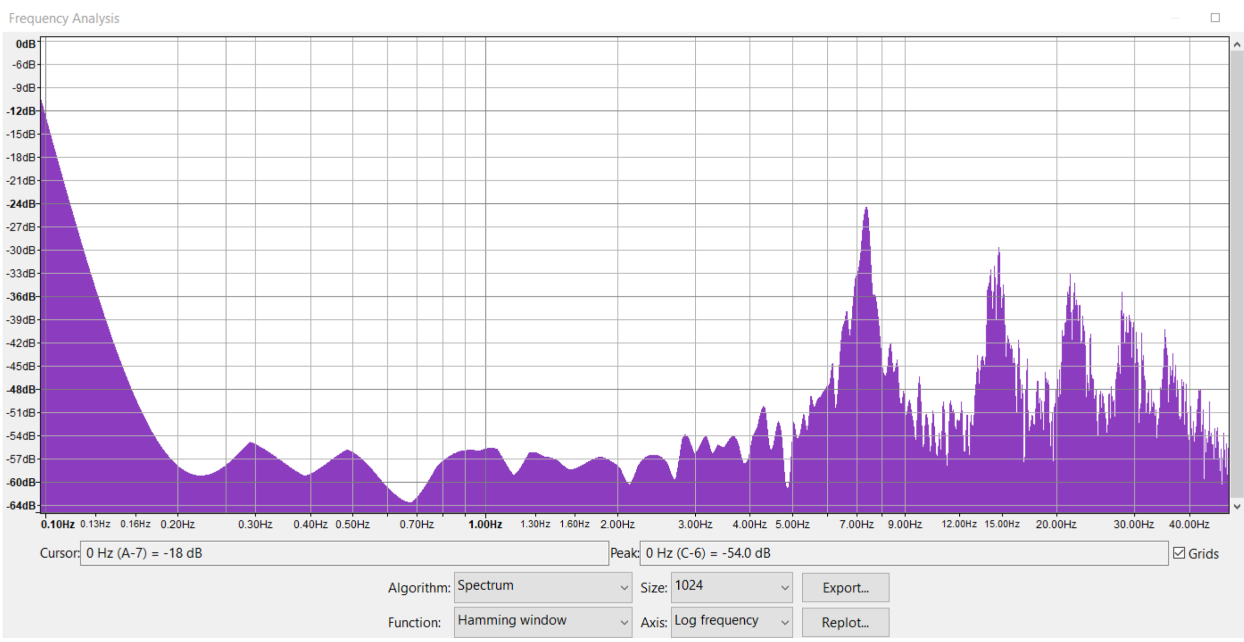


Figure 44. Frequency components of the brake pedal acceleration data for a test run at 55 mph in the 2012 Toyota Camry

This process was repeated for the vehicle acceleration data to determine if there were differences in the frequency distribution. Figure 45 shows the frequencies the vehicle experienced, which are nearly the same as the frequencies seen from the brake pedal (Figure 45).

Both the vehicle and the brake pedal had significant frequency components at approximately 7 Hz, 15 Hz, 22 Hz, 29 Hz, and 36 Hz. Since there were no meaningful differences observed between the brake pedal and vehicle frequency distributions, the vehicle sensor was removed from further analysis.

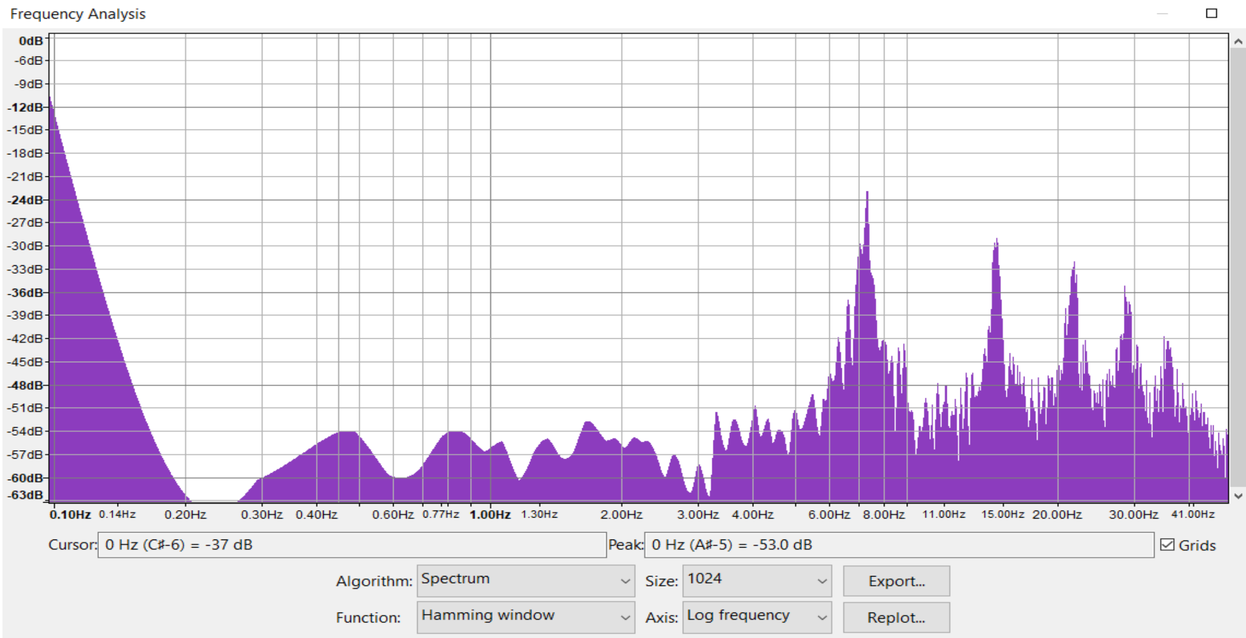


Figure 45. Frequency components of the vehicle acceleration data for a test run at 55mph in the 2012 Toyota Camry

Since the ABS task at the track uses BMWs rather than the older model Toyota Camry, therefore, accelerometer data were collected from both a 2021 BMW 240i and 340i using the same data collection and analysis procedures as were used with the 2012 Toyota Camry. The frequency components of the BMW 240i during ABS activation were found to be 8Hz, 15Hz, 23Hz, 31Hz, 39 Hz, and 46 Hz (see Figure 46).

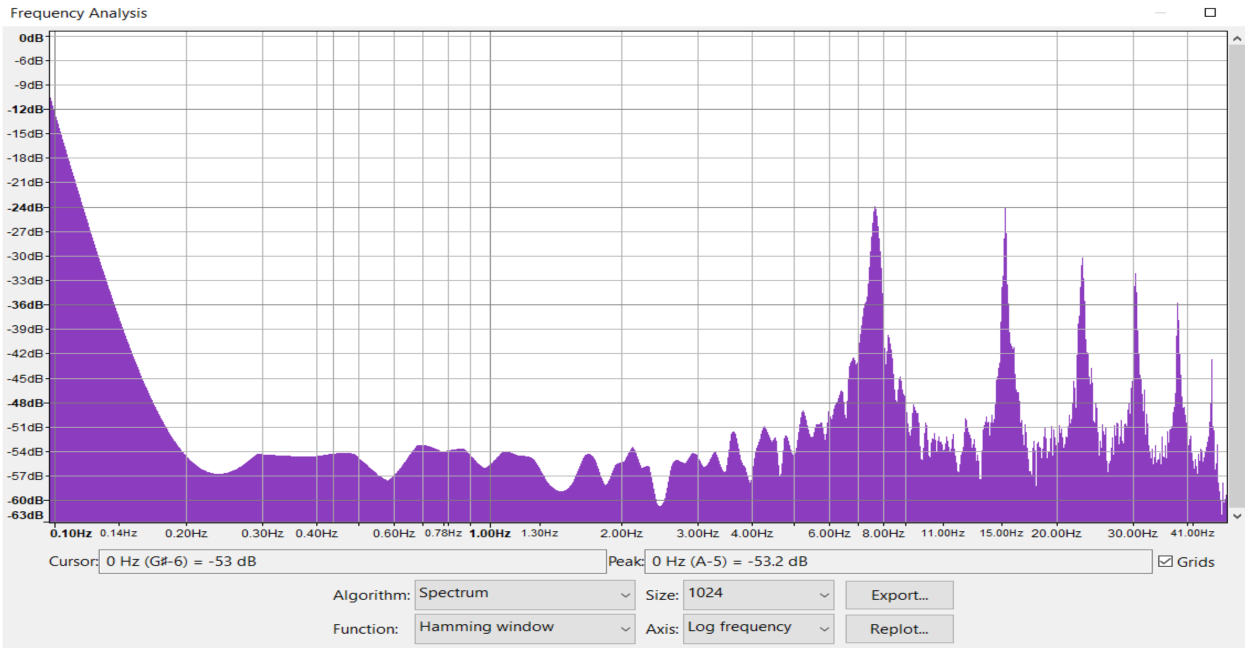


Figure 46. Frequency components of the brake pedal acceleration data for a test run at 55mph in the 2021 BMW 240i

The frequency components for the 2021 BMW 340i during ABS activation were 8Hz, 16Hz, 23Hz, 31Hz, 39 Hz, and 46 Hz (see Figure 47).

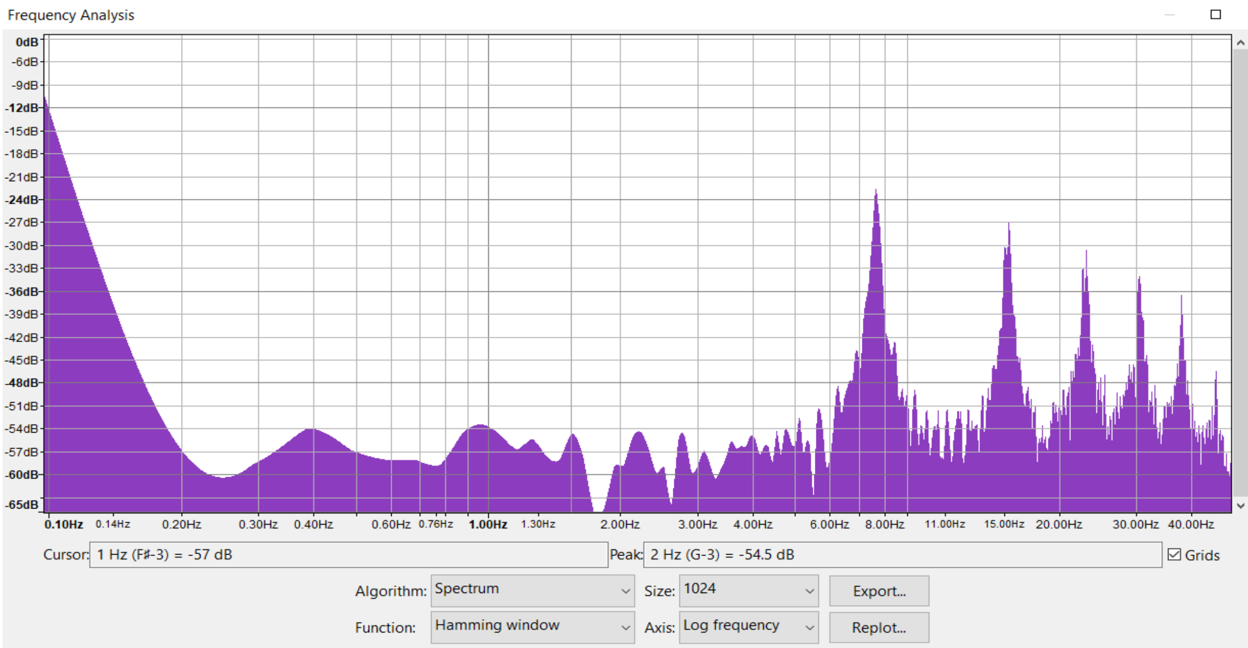


Figure 47. Frequency components of the brake pedal acceleration data for a test run at 55mph in the 2021 BMW 340i

9.2.1.2.3.2 ABS Feedback Audio File

Since the frequency components for the 2021 BMW 240i and 340i were so similar, one audio file was made to represent these two BMW vehicles. To make the audio file as an input for the ButtKicker, a raw input from the accelerometer (used to gain the frequency distribution) when ABS was activated was exported as a sound using Audacity.

9.2.1.2.4 Seat Selection

For this task, the simulator's intended use was for participants to practice emergency braking, which required participants to slam the brake pedal. As a result of this slamming, participants needed a seat that would allow for bracing while slamming and fully depressing the brake pedal. Due to the desire for a small footprint simulator, a simulator with an integrated seat was simply too large. Therefore, a chair was mounted to rails to prevent participants from tipping, the rails also eliminated the possibility of rotation (see Figure 48).

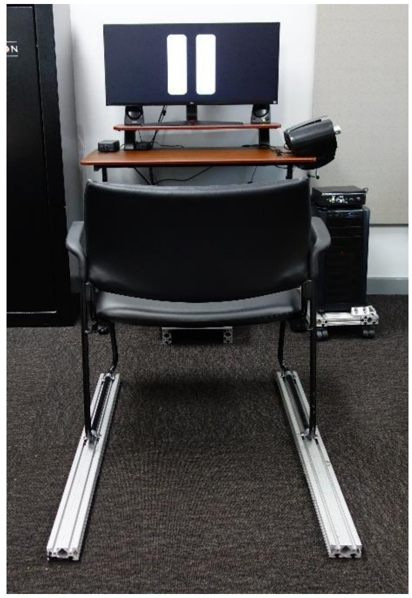


Figure 48. Chair mounted on rails to prevent tipping

9.2.1.2 Simulator Layout

For this simulator to be used to practice emergency braking in a pragmatic fashion, the pedal set and seat required a similar layout consistent with occupant packaging in vehicles. Since the participants are sitting in a chair instead of a vehicle seat, the simulator layout is based upon the packaging consistent with a pick-up truck (i.e., Ford F-150, Chevrolet Silverado 1500, etc.). The seat height in a pick-up truck is higher than a sedan or SUV, which is more consistent with sitting in a chair. For packaging requirements, a 2008 Ford F-150 was used as a reference. The seat height (H30) was determined by measuring the distance between the vehicle floor and the seating reference point (SgRP; see Figure 49).

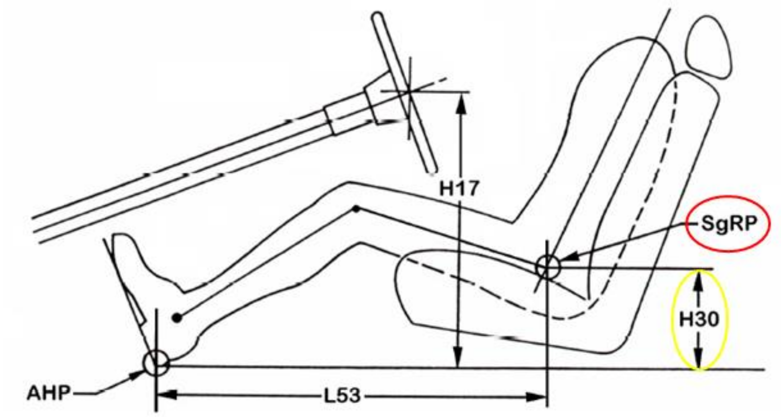


Figure 49. Seat height (H30 circled yellow) and the seating reference point (SgRP circled red; SAE, 2007)

To measure the seat height in an F-150, the seat was moved to the rear-most position to represent a 95th percentile male. To measure the seat height, an SgRP form was placed in the center of the seat (see Figure 50).

Figure 50. SgRP form in F-150 seat

A wooden dowel with a level at one end and a felt tip on the other, which was Velcroed to the SgRP point on the form, was used to measure the SgRP height from the floor (see Figure 51).

Figure 51. Seat height measurement in the F-150

The carpet height was measured and subtracted from the seat height measured to give a total seat height of 320 mm, which is consistent with the seat height range for pick-up trucks (300-350 mm; Macey & Wardle, 2014). The chair used for the ABS simulator's seat height is roughly 500 mm from the SgRP to the floor. To approximate the 320 mm seat height requirement, the pedal set was lifted 184 mm using aluminum extrusion to create a base for the pedal set, resulting in a final seat height of approximately 316 mm (see Figure 52).

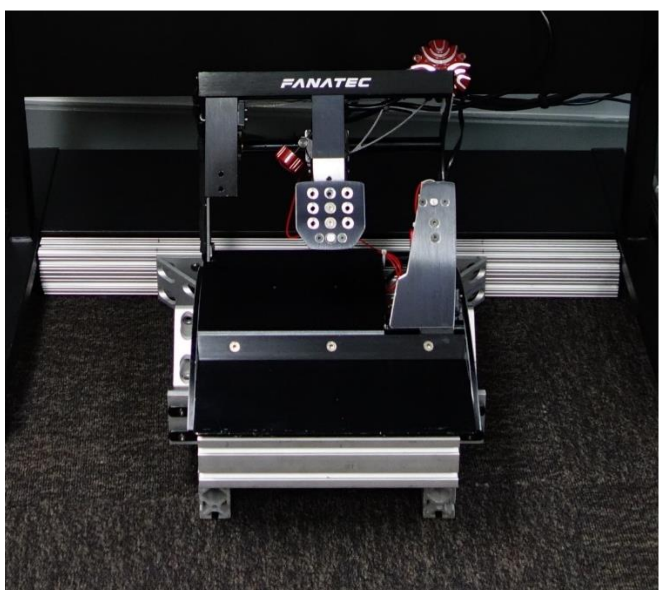


Figure 52. Pedal set with an aluminum extrusion base

A small height adjustable desk was used (Eureka LLC ERK-SW-40T). While the steering wheel position was taken into account from a packaging perspective, the CSL Elite Wheelbase was mounted to the side of the table since a steering wheel is not required for this task (see Figure 53).

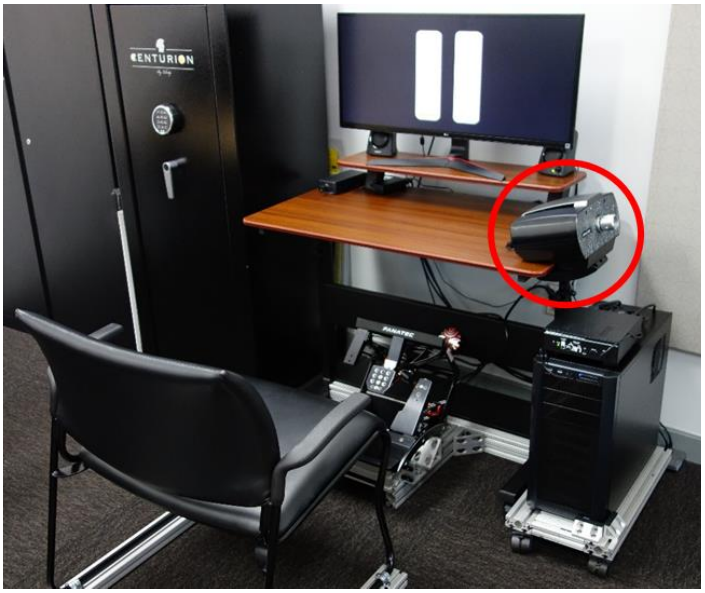


Figure 53. CSL Elite Wheelbase (circled in red) mounted to the side of the desk

9.2.1.2.6 DriveSafey CDS 200 ©

For the usability study, a *DriveSafey CDS 200* was used for the training tasks prior to the emergency braking task. The *CDS 200* © is a commercially available simulator featuring an instrument cluster, steering wheel and pedals from a Ford Focus (see Figure 54).

Figure 54. DriveSafety's CDS 200 © simulator

9.2.1.3 Interactive Exercises

DriveSafety’s SimClinic interactive exercises were used in this study focusing on the gas and brake pedal tasks. Interactive exercises use symbols rather than a driving scene; therefore, simulator sickness is not possible.

9.2.1.3.1 Pedals Static©

Pedals Static© is a DriveSafety interactive exercise which consists of static targets as visual representations on the gas and brake pedal (see Figure 55). The goal of this task is to press the gas or brake pedal to move the indicator into the target zone and hold the indicator in the target zone for three seconds. The targets move to different positions on the pedal while alternating between the gas and brake pedals. Level 2 of this interactive exercise was used, where the target zone is 25% of the size of the pedal. To “pass” this ask and move on to the next task, the participants need to make less than two errors (leaving the target zone).

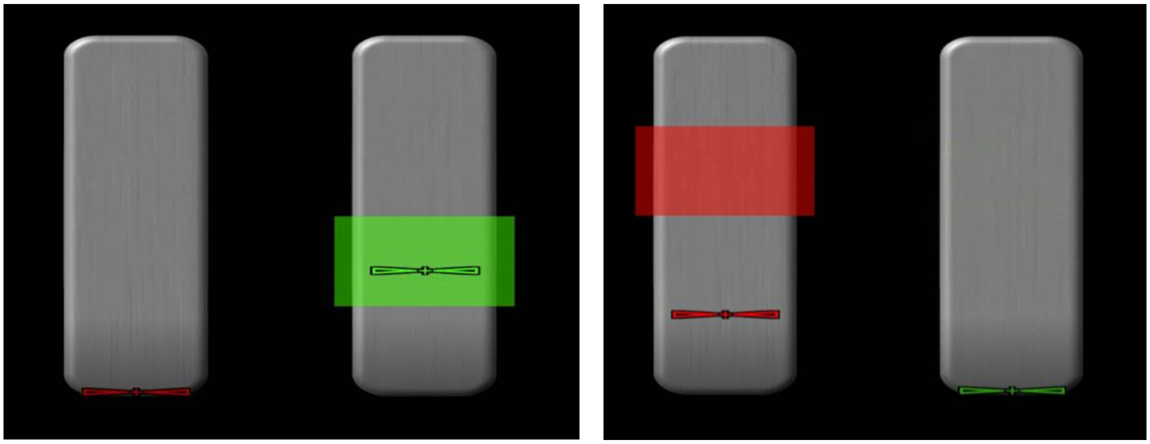


Figure 55. Pedals Static © Level 2 the left image shows the gas pedal target with the indicator in the target zone and right image shows the brake pedal target with the indicator outside of the target zone

9.2.1.3.2. Pedals Chase©

Pedals Chase© is a DriveSafety interactive exercise which uses of dynamic targets on the same visual representation of the gas and brake pedal (see Figure 56). The participant's goal is to keep the indicator in the target zone the target zone that 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 needs to make less than three errors (leaving the target zone) to move on.

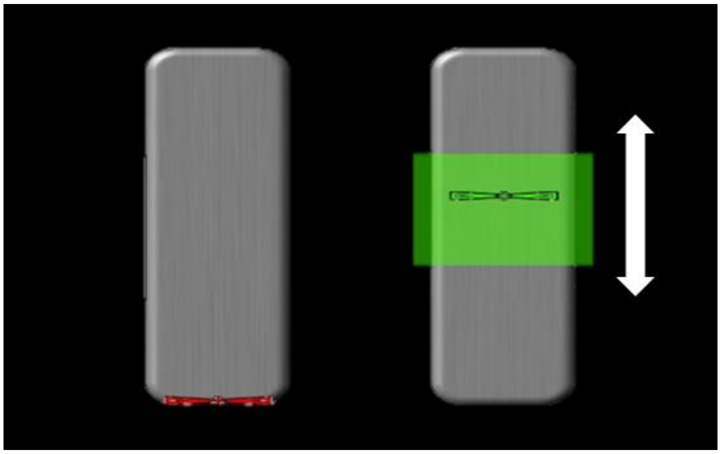


Figure 56. Pedals Chase© Level 2

9.2.1.3.3 Reaction Timer Stoplight©

Reaction Timer Stoplight© is a DriveSafety interactive exercise used to measure brake reaction times. To begin the interactive exercise, the gas pedal must be lightly pressed so the green light is illuminated, and the participant must maintain that pedal pressure. Once the stoplight changes from green to red, the participant should press the brake pedal quickly (see Figure 57). The time from releasing the gas pedal to pressing the brake pedals is recorded and displayed on the monitor. The scenario consists of a practice with four trials and three tests with four trials in each test. After the fourth trial an average is displayed for the practice or test.

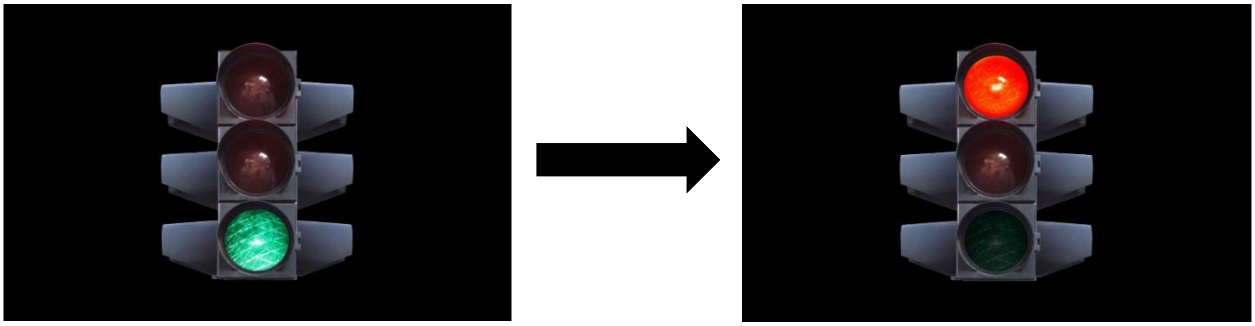


Figure 57. Reaction Timer Stoplight©

9.2.1.3.4 Pedals Emergency Stop©

The *Pedals Emergency Stop©* interactive exercise was motivated as a result of the Guard Your Life program where teens struggled with ABS activation. The interactive exercise looks identical to *Pedals Chase©* and begins with a moving target on the gas pedal (see Figure 58, left). The amount of time the gas pedal target is in motion until the brake pedal target zone appears was designed to vary to prevent the driver from anticipating the target. The number of times the gas pedal target crosses the middle of the gas pedal is randomized between a minimum of two times and a maximum of six times. When the brake target zone appears on the very top of the brake pedal (see Figure 58, right) and a loud, audible “Stop” prompts the participant to move the indicator in the target zone on the brake pedal.

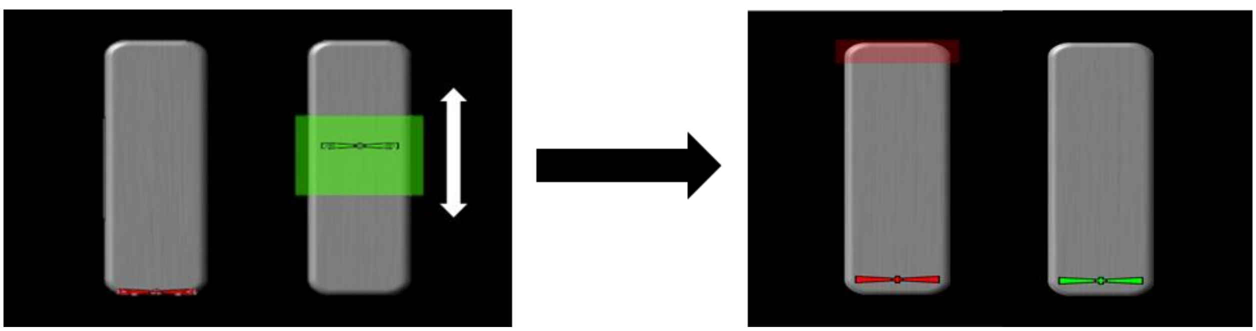


Figure 58. Pedals Emergency Stop© moving gas target (left) and brake target (right)

The target zone is located at the very top of the brake pedal (see Figure 59), and even, extends beyond the brake to encourage participants to press the brake pedal to the pedal’s maximum travel.

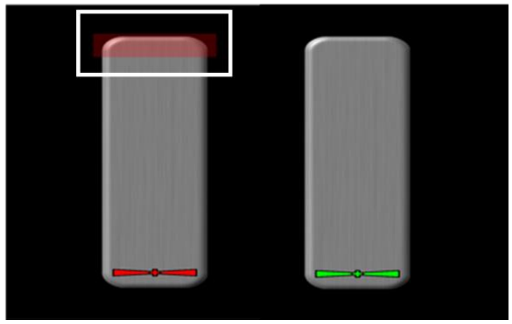


Figure 59. Location of the brake target zone

The goal for this task is to press the brake pedal fast and hard enough, as well as 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.

9.2.1.3.4.1 Triggering the ABS feedback

In order to activate ABS in a vehicle, the driver must quickly press the brake pedal near or at the maximum travel, then maintain that pressure to keep ABS activated throughout the stop. ABS is activated due to a wheel approaching a locked state. ABS monitors the rotation speed of the tire to determine if a wheel is slipping (not rotating). The simulator, unlike a vehicle, cannot base ABS activation off of dynamic factors such as vehicle speed, vehicle weight, tire type, road surface, etc. The simulator rather monitors brake pedal position and the rate of change of the brake pedal position. The trigger logic for when the simulator needed to send the ButtKicker the audio file to play, was dependent on the brake pedal inputs.

As part of NHTSA's Light Vehicle ABS program, Task 4 aimed to evaluate how ABS performed on various surfaces and with multiple maneuvers. The study used a professional test driver to minimize any differences in driver behavior. To maintain consistency, the study specified that the minimum force the test driver needed to press the brake pedal in order to activate ABS, which was 667 N (Forkenbrock, Flick & Garrott, 1999). From the minimum brake pedal force to activate ABS, as determined by NHTSA, it was possible to approximate the required rate of change of the brake pedal.

The force used when a driver presses the brake pedal consists of the mass of the driver's leg and foot as well as the corresponding acceleration of the brake press. NHTSA's Task 4 does not specify the leg and foot weight of the test driver (Forkenbrock, Flick & Garrott, 1999). For automotive vehicle packaging, typically 95th percentile males, 5th percentile females and 50th percentile males are used to represent the spectrum of occupants. To represent the spectrum of drivers the leg and foot mass from the 95th percentile male (15.998 kg), 50th percentile male (13.316 kg), and 5th percentile female (9.763 kg) were used (Human Solutions, 2021). To determine the acceleration of the brake press, the leg and foot mass were divided from the force (667 N) for an acceleration value of 41.692 m/s^2 for the 95th percentile male, 50.090 m/s^2 for the 50th percentile male, and 68.319 m/s^2 for the 5th percentile female. Acceleration of the brake press is comprised of the distance of pedal travel over the time of the brake press then squared. The brake pedal travel of the Fanatec ClubSport V3 inverted brake pedal is 1.75 in or 0.04445 m. Dividing the brake pedal travel by the acceleration value yields time squared. After taking the square root of the time, the resulting number is the time it takes to press the brake pedal to achieve the required force of 667 N. The minimum time it takes to press the pedal to the maximum input to activate ABS is 0.032 s for the 95th percentile male, 0.030 s for the 50th percentile male, and 0.026 s for the 5th percentile female. The average time it takes to fully depress the brake when activating ABS between the three percentiles is 0.03 s. In order to press the brake pedal quickly enough to activate ABS on the simulator, the time from pressing the brake until the indicator is in the target zone should be approximately less than 0.03 s.

A subject matter expert, who is a professional race car driver and driving instructor who teaches ABS activation multiple times a week, verified the timing and feel of ABS activation on the simulator. The subject matter expert determined that the 0.03 s time requirement was too difficult to achieve. The time was increased to 0.035 s, which the subject matter expert confirmed feels similar to when ABS is activated in a vehicle. The 667 N minimum force on the brake pedal required for the driver to activate ABS as determined by Forkenbrock, Flick & Garrott (1999) does not take into account the resistance of the brake pedal, which could be why the 0.03 s time requirement was too difficult.

From the earlier study where instructors rated drivers' performance activating ABS (Mims et al., 2021), there were three common scenarios where drivers either fully activated ABS, partially activated ABS, or did not activate ABS (see Table 28). In the *Pedals Emergency Stop*© interactive exercise, the location of the target zone encourages participants to press the brake pedal far enough to activate ABS. In a vehicle, if the driver does not press the pedal quickly, but presses the pedal to the maximum travel, ABS will be delayed but will activate. If a participant eases onto the brake pedal during the *Pedals Emergency Stop*© interactive exercise, not meeting the 0.035 s threshold, the ABS feedback from the ButtKicker is delayed. The last common scenario from the track is when a driver releases pressure from the brake pedal where ABS is no longer activated. During the *Pedals Emergency Stop*© interactive exercise, if the brake indicator leaves the target zone, the ABS feedback will be disabled.

Table 28. Common scenarios from the track ABS exercise (Mims et al., 2021), the action needed to improve performance and how action was incorporated into the Pedals Emergency Stop© interactive exercise

Instructor rating	Instructor feedback	Scenario in vehicle	Needed action	Action in *Pedals Emergency Stop ©*
1	Press the brake harder or as hard as you can	Does not press brake hard enough to lock the wheels, ABS does not activate	Press the pedal to the maximum travel	Target zone located at 95% of the pedal travel
3 or 4	Slam the pedal from the start instead of easing onto it	Eases onto the brake pedal before getting the wheels to lock, activating ABS	Slam on the pedal from the start	Haptic ABS feedback is delayed
3 or 4	Press the pedal and keep it pressed until the vehicle comes to a complete stop	Initially presses the brake pedal fast enough to maximum to activate ABS, but releases pressure disabling ABS	Maintain brake pedal throughout the stop	Leaves target zone, haptic ABS feedback disabled
5	No feedback (fully activated ABS)	Presses brake pedal hard enough to activate ABS and maintains brake pedal pressure throughout the stop	None	Haptic ABS feedback is enabled once in the target zone and remains on for three seconds

To trigger the haptic ABS feedback, the brake indicator must be in the target zone. The participant must press the pedal moving the indicator into the target zone under the 0.035 s, triggering the ABS feedback instantly. If the participant does not press the brake pedal within 0.035s, the ABS feedback is not instant, which corresponds to an instructor rating of 3 or 4, where the participant eased onto the brake pedal. Since the time to hold the indicator in the target zone is only three seconds, or three tones, a delay of one second was selected to allow participants who do not press the pedal fast enough to gain experience with the haptic ABS feedback. The haptic ABS feedback trigger logic is displayed in the flowchart below (Figure 60).

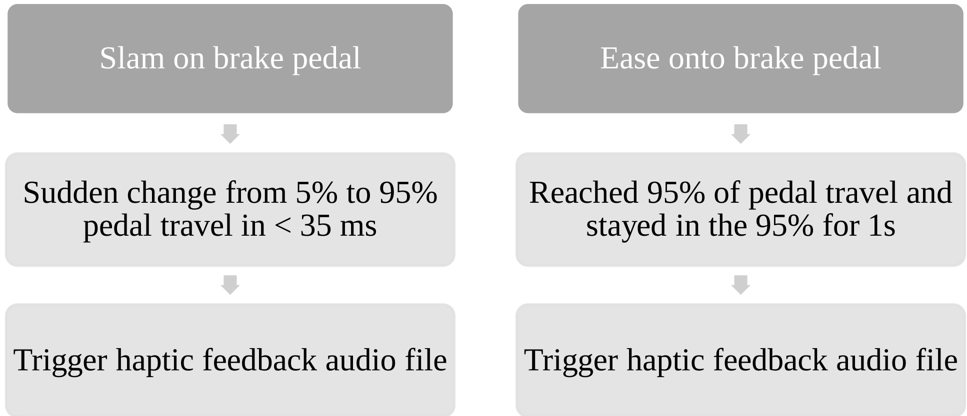


Figure 60. Haptic ABS feedback trigger logic flowchart

9.2.1.3.4.2 Pedals Emergency Stop© Results

After each brake attempt throughout the *Pedals Emergency Stop*© interactive exercise, the results page displayed the participant's performance for each attempt (see Figure 61).

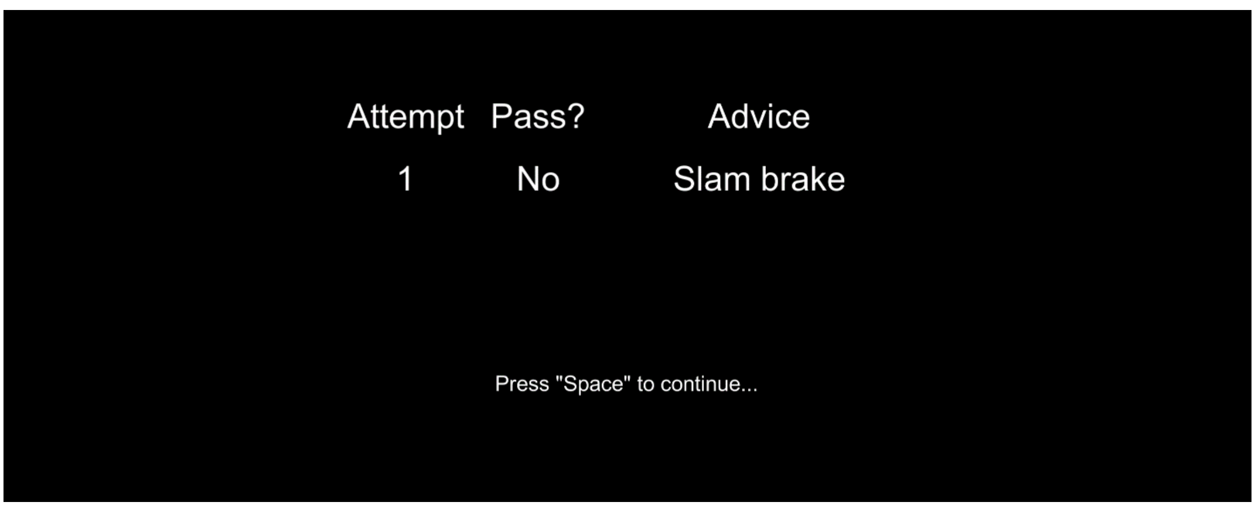


Figure 61. Example results after first target of the Pedals Emergency Stop© interactive exercise

Information was displayed in three columns. The column on the left labeled "Attempt" showed the order of brake targets. The middle column labeled "Pass?" indicated if a person passes or fails the performance activating ABS for each brake target. If a "Yes" was displayed, the participant pressed the pedal fast enough and held the indicator in the target zone for the full three tones. If a “No” was displayed, the 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 right column labeled “Advice” aimed to help the participant understand how to improve their performance if they did not receive a “Yes” in the “Pass?” column. If the participant did not press the pedal fast enough to instantly trigger the haptic ABS feedback, “Slam brake” 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, “Slam brake” was presented. Figure 61 above shows an example of possible results after completion of the first attempt to activate ABS, where the participant did not pass and received the feedback to “Slam brake”. On the track, when the instructor gave feedback to the drivers after rating their performance activating ABS (Mims et al, 2021), the feedback during the first few runs focused on pressing the pedal hard enough to activate ABS or slamming on the pedal instead of easing onto it. As the drivers completed more runs, the feedback from the instructors shifted towards pressing the pedal until the vehicle came to a complete stop. 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.

After viewing the result of the first attempt to activate ABS, the task started over for the next attempt. The performance result for the second attempt was then presented on the screen. This process was repeated for a total of five targets. At the end of the interactive exercise, a summary page with the results from all five attempts was displayed (see Figure 62).

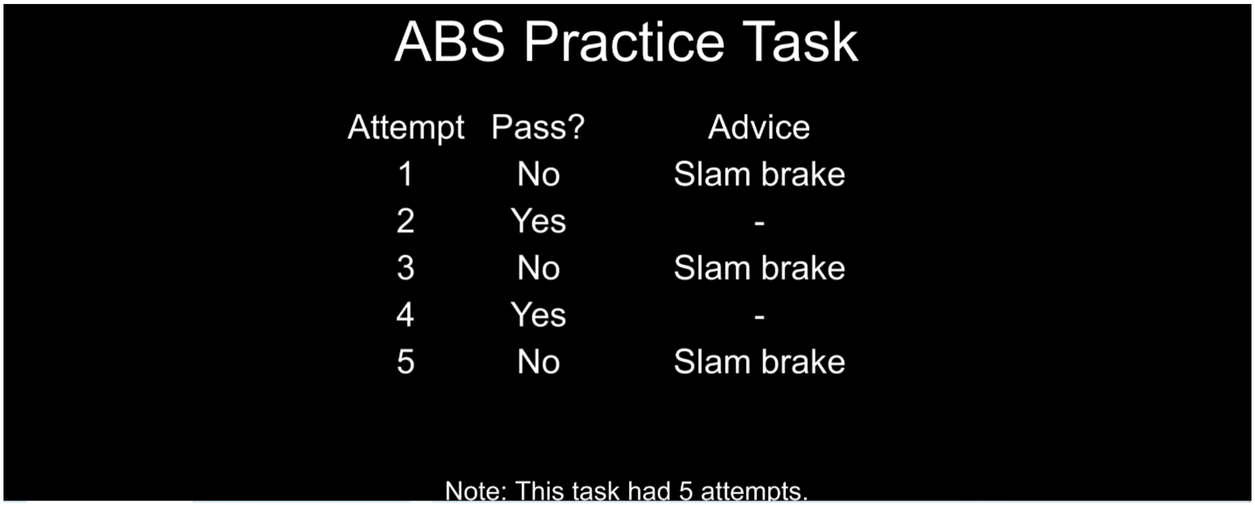


Figure 62. Example results page after all five targets of the Pedals Emergency Stop© interactive exercise

9.2.1.4 Procedure

Prior to consent, participants were asked they understood what the driver feels when ABS is activated for grouping.

All subjects read the consent form and provided their consent prior to participating in this study. 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).

After being consented, participants were fitted to the DriveSafey CDS 200 simulator by adjusting the table height, distance from the seat to the pedals, and distance the steering wheel was from the participant. Using the CDS 200, the participants completed *Pedals Static*© with no more than 2 errors, *Pedals Chase*© with no more than 3 errors, and *Reaction Timer Stoplight*© with an average no greater than 0.7s (Brooks et al., 2016).

Next, the participants moved to the simulator with ABS feedback to complete the *Pedals Emergency*© interactive exercise. Prior to completing the exercise, the participant adjusted themselves to a comfortable distance from the pedals, where they were able to press both pedals to maximum travel. Participants were separated into two different groups, completing the study in one of two orders. Half of the participants completed the first attempt of *Pedals Emergency Stop©* interactive exercise without an explanation of ABS or the feedback from the simulator, while the other half received the explanation of ABS before the *Pedals Emergency Stop©* interactive exercise. Both groups performed the *Pedals Emergency Stop©* interactive exercise three times for 15 trials.

The participants who completed the first attempt of the *Pedals Emergency Stop©* interactive exercise without an explanation of ABS, were given the following instructions: "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 and you hear “Stop”, press the brake as quickly as possible to move into the target zone. Hold the indicator in the target zone for 3 tones. Do you have any questions?"

After completing the first brake target and feeling the haptic ABS feedback for the first time, the participants were asked if they knew what the feedback or vibration from the simulator represents. Then, participants were given an explanation of ABS and the feedback: "The vibration from the simulator represents the feedback you would experience from the anti-lock braking system (ABS). In an emergency braking scenario, ABS activates to prevent the wheels from locking up, which can cause skidding and loss of steering control. ABS quickly holds and releases brake pressure, which is what you feel as a result of the system activating. To activate ABS, you must stomp on the brake pedal by lifting your right foot up from the gas pedal, moving it above the brake pedal and pressing the pedal all the way down as quickly as possible. Once you have pressed the brake pedal all the way down, maintain pressure on the brake pedal until you hear three tones. In a real vehicle it will take time for the vehicle to come to a complete stop, so that is why maintaining the brake pedal pressure is important to stop in the shortest possible distance." Participants were then asked to practice the movement from the gas to the brake pedal five times prior to the next attempt.

After the explanation of the feedback, the researcher provided an explanation of the results page: "This screen shows how you did pressing the brake pedal to activate ABS. 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 hard enough and held the indicator in the target zone for 3 tones you will pass. If you didn’t press the brake pedal hard enough or didn’t hold the brake indicator in the target zone for enough time, you will not pass. The column on the right labeled “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 hard enough, you will get the advice to slam the pedal. If you do not hold the indicator in the target zone for 3 tones, you will get the advice to hold longer.” The researcher then asked the participant to explain how they performed during the first attempt. The participant continued through the remaining four targets, explaining how they performed on each attempt.

For the remaining 10 of the total 15 attempts, the instructions reiterated to slam on the brake pedal and hold the indicator in the target zone for three tones. Completing 15 trials of the interactive exercise, allowed the participants to practice the braking behavior associated with ABS after benefitting from the explanation. During the ABS exercise on the track (Mims et al., 2021), drivers had an average of seven runs to practice activating ABS on the track. Including a protocol that delayed the explanation of ABS after the first attempt of *Pedals Emergency Stop©*

allowed for and understanding of how the participants reacted to both the stomping prompt and the haptic ABS feedback in the exercise.

To understand how many practice attempts were necessary, explaining ABS and the haptic feedback before *Pedals Emergency Stop*© was necessary. Participants in this group received the same explanation of ABS and the haptic feedback they would experience. After completing the first attempt of the *Pedals Emergency Stop*© interactive exercise, participants received the explanation of the results. Participants completed the *Pedals Emergency Stop*© interactive exercise two more times for a total of 15 trials, to provide the same number of trials as the group that received the explanation of ABS after the first attempt of the *Pedals Emergency Stop*© interactive exercise.

9.2.1.4.1 Interview

At the end of the study, participants completed an interview which consisted of questions to understand the participants prior experience with ABS, the feel of the ABS feedback from the simulator, the *Pedals Emergency Stop*© interactive exercise and overall usability of the simulator.

The interview began with questions to understand the participants prior experience with ABS beyond their initial grouping. Due to the large age range of the participants, it was possible that some of the participants were taught to pump the brake pedal when learning how to drive, which is an action necessary for emergency braking situations for vehicles without ABS. Therefore, participants were asked if they pumped the brake pedal during emergency braking events to potentially identify individuals who may be outliers. The results from the track study evaluating instructor ratings of ABS performance (Mims et al., 2021), found that participants who reported practicing or being trained to activate ABS had significantly higher performance ratings compared to other participants. For this reason, participants in the current study were asked if they had practiced or been trained to activate ABS to determine if they outperform the other participants with prior experience.

The next section of the interview evaluated the haptic ABS feedback from the simulator. To validate the ABS feedback from the simulator, the group of participants that had knowledge of the feel of ABS when activated, were asked to evaluate the feel, sound, and the difficulty to activate ABS in the simulator in comparison with past experiences activating ABS in a vehicle.

Next, the interview questions focused on the *Pedals Emergency Stop*© interactive exercise and procedures. Participants were asked if the *Pedals Emergency Stop*© interactive exercise prompted them to press the brake pedal hard enough to activate ABS in order to earn a "pass" as well as the interactive exercise instructions. Participants were asked if the location and size of the target zone as well as the audible "Stop" and loudness of the "Stop" prompted them to press the brake pedal hard enough to activate ABS.

Participants were asked to read the interactive exercise's instructions, explanation of the ABS feedback, explanation of the results, and the advice given based on performance and provide clarifications. Participants were asked to describe the hardest part of activating ABS during the interactive exercise. During the study, participants completed the *Pedals Emergency Stop*© interactive exercise three separate times, resulting in a total of 15 attempts. Participants were asked if they had enough attempts or if they wanted more practice; if someone wanted more practice, they were asked how many more attempts.

The last portion of the interview was inspired by the System Usability Scale (SUS; Brooke, 1996). The SUS is a method to measure usability, where participants respond to statements using a five-point Likert scale ranging from strongly agree (rating of 1) to strongly disagree (rating of 5). One statement from the SUS was modified and additional statements were added (see Table 29).

Table 29. Statements participants responded to using a 1-5 scale, where a rating of 1 is strongly agree and a rating of 5 is strongly disagree

Question	Response option
I found the ABS practice unnecessarily complex.	SUS 1-5 scale
I found the ABS practice task to be a practical tool.	SUS 1-5 scale
I think my understanding of ABS was improved from the ABS practice task.	SUS 1-5 scale
I feel as though I will practice using ABS in a vehicle after using the ABS practice task.	SUS 1-5 scale
I would recommend the ABS practice task for new drivers.	SUS 1-5 scale
I would recommend the ABS practice task for refresher training.	SUS 1-5 scale
I would recommend the ABS practice task for evaluating fitness to drive.	SUS 1-5 scale

The italicized statement was adapted from the original SUS.

Lastly, the participants were asked for any additional suggestions to improve the simulator or study. The participants were then given a $15 Visa gift card in exchange for their participation and the study was concluded.

9.2.1.5 Data Organization and Analysis

The data for all simulator interactive exercises and the interview responses were combined and organized by participant. The number of "passes" from *Pedals Emergency Stop©* was evaluated for each participant and then for each of the two groups. The responses to each of the interview questions were sorted and grouped by similar responses to form categories. Once the categories were formed, the number of responses in each category were tallied for comparison across all categories.

9.2.2 Results

9.2.2.1 Pedals Emergency Stop©: First Attempt

For the first attempt of the *Pedals Emergency Stop©* interactive exercise only four of the 24 participants “passed”. Of the participants who passed, two participants had prior experience feeling ABS activate and two did not have any experience activating ABS. Three of the four participants that passed on the first attempt received the explanation of ABS and the feedback prior to completing *Pedals Emergency Stop©*.

Twenty of the participants did not pass on the first attempt of *Pedals Emergency Stop©*. Five of the participants were startled by the audible “Stop” and/or the haptic ABS brake pedal feedback. Three of the participants did not receive the haptic feedback during their first attempt of *Pedals Emergency Stop©*. These participants did not press the brake pedal fast enough to meet the 0.035 s requirement, causing the haptic feedback to be delayed by one second, but they held the indicator in the target zone less than one second, thus leaving the target zone before the haptic ABS feedback began. All three participants received the haptic feedback during the second attempt. One participant used their left foot to brake during the first attempt of *Pedals Emergency Stop©* but did not press the brake pedal fast enough to pass; this participant did not use their left foot for remaining attempts. All twenty participants received the advice to “Slam Brake”.

9.2.2.2 Pedals Emergency Stop©: All Attempts

Though only four participants received a pass during their first attempt of *Pedals Emergency Stop©*, as the number of attempts increased, the number of participants that passed grew (see Figure 63). During the second attempt 11 participants passed, 16 participants passed on attempt three, 19 participants passed on attempt four, and 20 participants passed on attempt five. A total of 18 participants passed on attempt six but attempt six was the first attempt of the second time through *Pedals Emergency Stop*©. Performance on attempts seven through 10 was consistent, ranging from 20 to 21 participants passing per attempt. Attempt eleven showed a similar trend to attempt six, where the number of participants that passed slightly dipped (18) during the first target of the third time through *Pedals Emergency Stop*©. The number of participants that passed during attempts twelve through fifteen ranged between 20 to 22 participants. Attempt 15 showed the highest number of participants that passed (22).

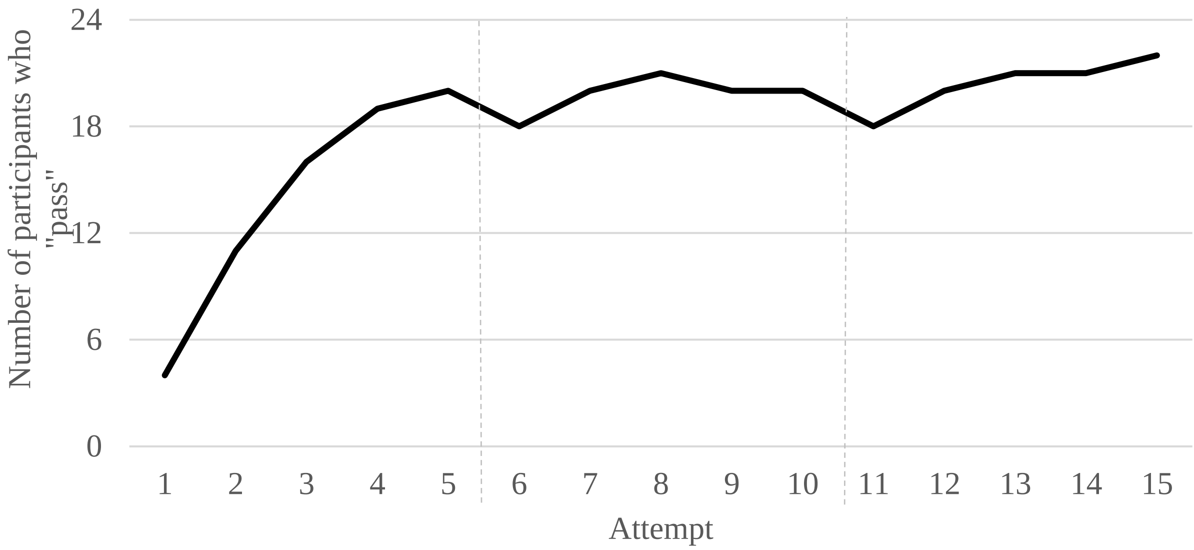


Figure 63. Number of participants that passed each attempt of Pedals Emergency Stop©. Note: the dotted lines represent the pauses between each trial of Pedals Emergency Stop©.

The majority of participants were able to receive a pass within the first five attempts of *Pedals Emergency Stop*©, averaging 3 attempts to receive a pass (see Figure 64). Four participants passed during the first attempt, nine participants passed during the second attempt, five participants passed during the third attempt and two participants passed during both the fourth and fifth attempts. One participant did not receive a pass until the fourteenth attempt and another participant did not receive a pass during the fifteen attempts. The participant that was not able to receive a pass during the fifteen attempts requested additional attempts, where they were able to pass during attempt eighteen.

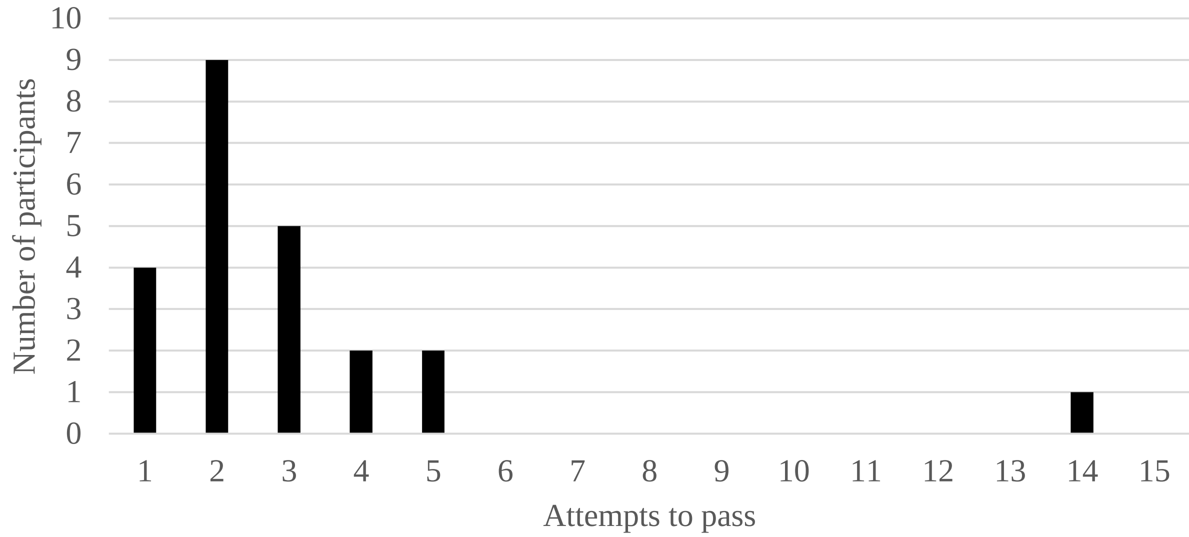


Figure 64. Number of attempts needed to receive a pass during Pedals Emergency Stop©. Note: One participant never received a pass during the 15 attempts.

9.2.2.2.1 Differences Between Participants with or Without Prior Experience Feeling ABS Activation

Participants were grouped based on their previous experience feeling ABS activate. There were 12 participants that had previously experienced the feel of ABS when activated and 12 participants that did not have experience feeling ABS. There were differences observed between participants with and without prior experience feeling ABS activate, primarily in the first five attempts (see Figure 65). For attempt one, four participants passed, where two (17%) had prior experience feeling ABS activate and two (17%) did not have experience with ABS. Attempt two showed a larger difference between those with and without ABS experience, where eight (67%) participants with ABS experience passed and three (25%) participants without ABS experience passed. The third attempt showed that nine (83%) participants with ABS experience passed and seven (58%) without ABS experience passed. Ten (83%) participants with prior ABS experience passed and nine (75%) participants without ABS experience passed during their fourth attempt. For attempt five, 10 (83%) participants with and without ABS experience passed. The number of participants in each ABS experience group became more consistent over the remaining attempts.

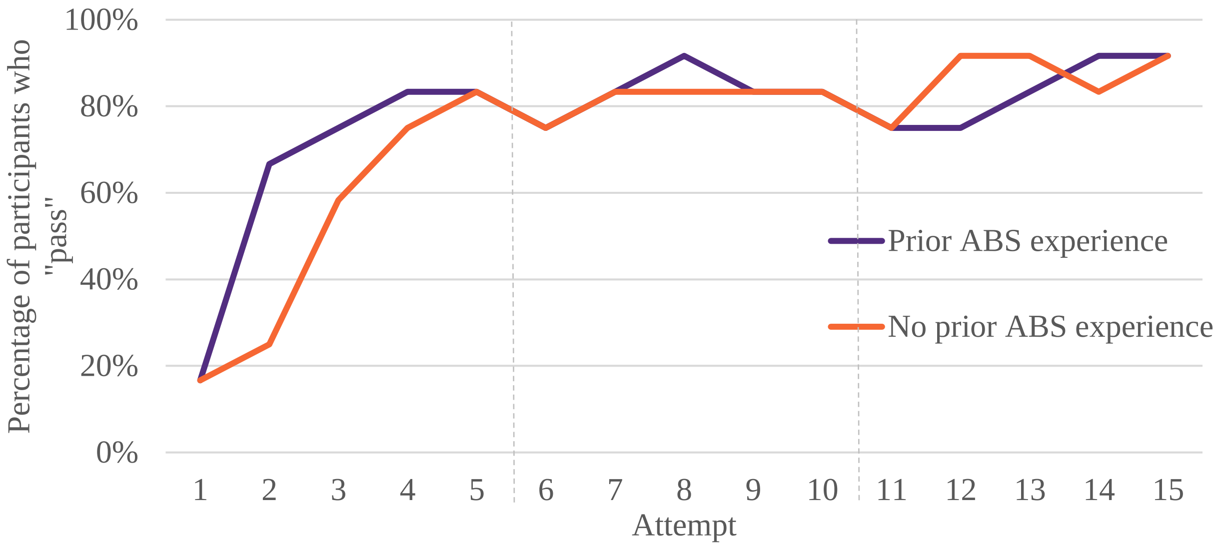


Figure 65. Percentage of participants with and without prior experience feeling ABS activate that pass each attempt of Pedals Emergency Stop©.
Note: the dotted lines represent the pauses between each trial of Pedals Emergency Stop©.

For the number of attempts it took participants to receive a pass, the participants with prior experience had more passes in fewer attempts compared to the participants without prior ABS experience (see Figure 66). All but one participant with prior experience feeling ABS activate, received a pass within the first three attempts. For participants without prior experience feeling ABS, all but one participant, received a pass within the first five attempts. One participant without prior ABS experience was not able to pass within the 15 attempts.

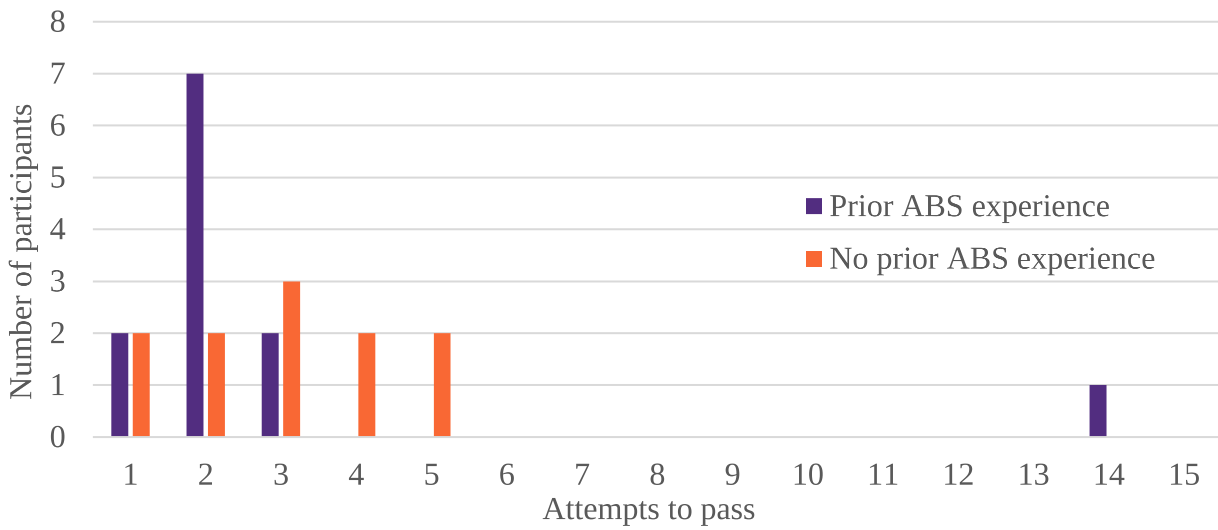


Figure 66. Number of attempts to pass for participants with and without prior experience feeling ABS activate.

Note: One participant with no prior ABS experience never received a pass during the 15 attempts.

9.2.2.2.2 Differences Between Participants That Received the Explanation of ABS and the Feedback Prior to Pedals Emergency Stop© or After the First Attempt

Participants were grouped by when they received the explanation of ABS and the feedback. There were 11 participants that received the explanation on ABS prior to the *Pedals Emergency Stop©* interactive exercise and 13 participants that received the ABS explanation after the first attempt. The participants that received the explanation before *Pedals Emergency Stop©* consistently passed more than the participants that received the explanation of ABS after their first attempt (see Figure 67). The first attempt showed that three of the four that passed, were part of the group that received the explanation of ABS prior to *Pedals Emergency Stop©*.

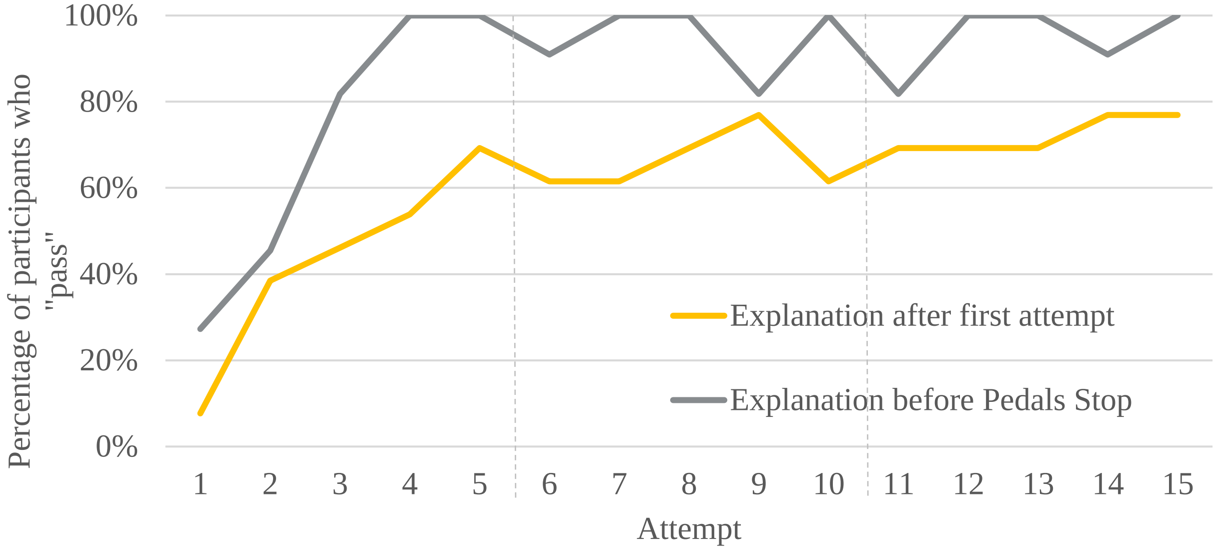


Figure 67. Percentage of participants that received the explanation of ABS before Pedals Emergency Stop© versus participants that received the explanation of ABS after the first target of Pedals Emergency Stop©.

Note: The dotted lines represent the pauses between each trial of Pedals Emergency Stop©.

Participants that received the explanation of ABS before *Pedals Emergency Stop©* also were all able to pass within the first four attempts (see Figure 68). All but two participants from the group that received the explanation of ABS after the first attempt of *Pedals Emergency Stop©*, passed within the first five attempts. For the two participants that did not receive a pass within the first five attempts, one participant passed once on attempt 14 and the other participant did not pass within the 15 attempts.

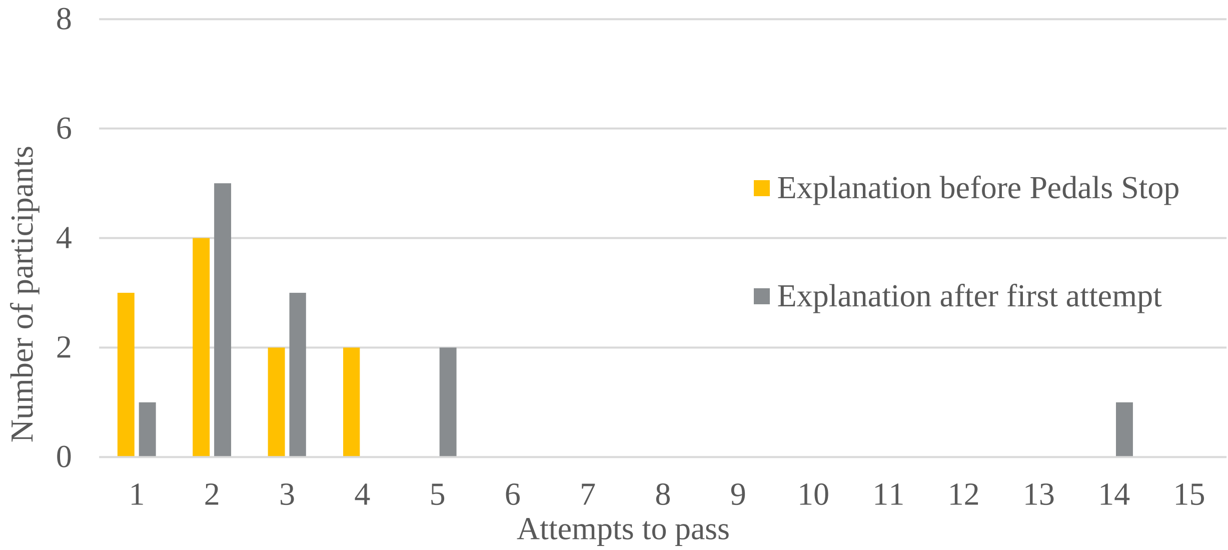


Figure 68. Number of attempts to pass for participants that received the explanation of ABS before Pedals Emergency Stop© versus participants that received the explanation of ABS after the first target.

Note: One participant who received the explanation of ABS after the first attempt never passed during the 15 attempts.

9.2.2.2.3 Differences Between Participants with and Without Prior ABS Experience as well as Participants That Received the Explanation of ABS and the Feedback Prior to Pedals Emergency Stop© or After the First Attempt of Pedals Emergency Stop©

When comparing the passing percentage between participants based on prior ABS experience and protocol grouping, the participants that received the explanation of ABS before *Pedals Emergency Stop*© had a higher percentage of participants than those who received the explanation of ABS after the first attempt of *Pedals Emergency Stop*© regardless of prior ABS experience (see Figure 69).

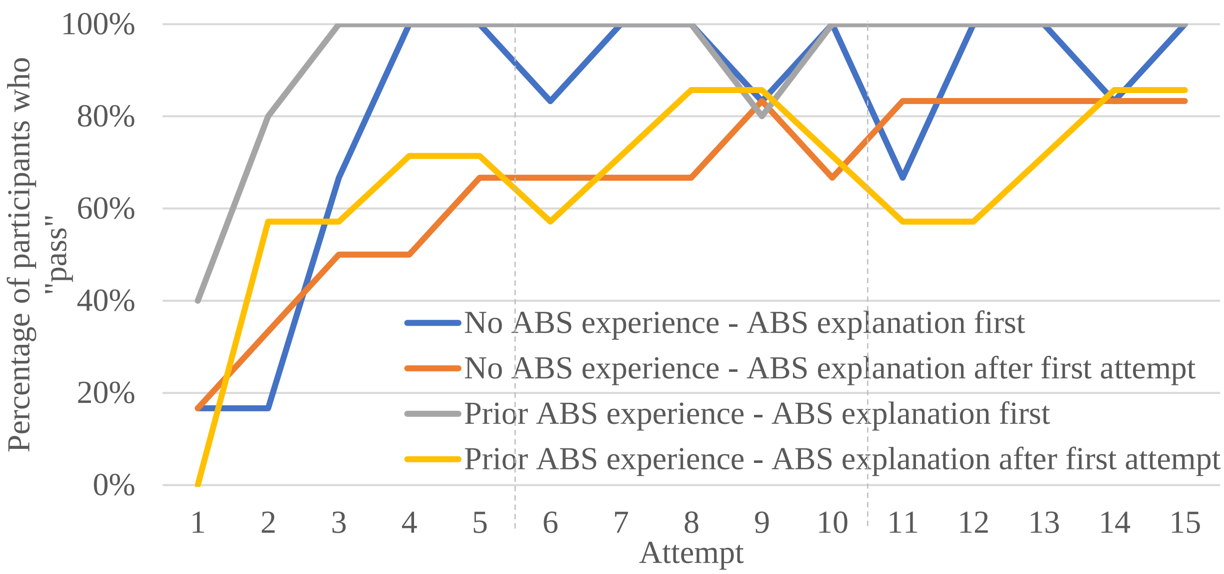


Figure 69. Difference in the percentage of passes for each attempt for participants grouped by prior ABS experience and protocol grouping

Note: the dotted lines represent the pauses between each trial of Pedals Emergency Stop©.

9.2.2.3 Pedals Emergency Stop©: Interactive Exercise Feedback (Advice)

All but one participant, who passed during every attempt of *Pedals Emergency Stop*©, received the feedback to "Slam brake", totaling 87 times "Slam brake" appeared. None of the participants received the feedback to "Hold longer" during *Pedals Emergency Stop*©. Since the participants only saw one piece of advice at a time and "Slam brake" was prioritized over "Hold longer", anytime the participants would have received the advice to "Hold longer" due to not holding the indicator in the target zone for three tones, the participant also did not press the brake pedal hard enough and received the advice to "Slam brake". During attempt one of *Pedals Emergency Stop*©, seven participants that received the advice to "Slam brake" also did not hold the indicator in the target zone for three tones, thus both advice options, to "Slam brake" and "Hold longer" applied.

9.2.2.4 Interview Results

9.2.2.4.1 Prior Experience with ABS

When participants were recruited, they were asked if they had experience with ABS and what they experienced when ABS was activated to ensure that the participant had experience activating ABS and was not confusing ABS with another component. There were 12 participants that had previous experience feeling ABS activate and 12 participants that did not have experience activating ABS. Of the 12 with prior ABS experience, five participants reported practice activating ABS and two reported ABS training. Of the 12 participants that did not report experience activating ABS, two participants reported that they had experienced ABS once or twice after feeling the ABS feedback from the simulator. These two participants were kept in the group without prior ABS experience because they did not know what ABS feels like activated prior to the study, essentially responding incorrectly to the question. During recruitment, one participant said they had experienced ABS activation in a vehicle but when asked what ABS feels like when activated, they responded incorrectly, and were grouped with the participants without ABS experience. The grouping process worked as anticipated.

9.2.2.4.2 Evaluation of ABS Feedback

For the participants that had previously experienced the feel of ABS when activated, they were asked to evaluate the feel, sound and difficulty of the ABS activation on the simulator. Seven of the 12 (58%) participants with previous ABS experience thought the feel of ABS on the simulator was similar to what they experienced in a vehicle during ABS activation. Five of the participants thought the feedback from the simulator didn’t feel similar, where three participants thought the vibration was more intense in the simulator than in a vehicle and two of the participants thought the frequency was too low in the simulator. Six (50%) of the participants thought the sound associated with ABS activation on the simulator sounded similar to what they have previously experienced in a vehicle and six thought it was different. Three of the participants thought the sound of ABS activating on the simulator was louder than in a vehicle and two participants identified a rattling sound from the simulator that was different from the sounds of ABS in a vehicle. Two of the participants identified that the simulator may be louder because there is no damping of the ABS feedback on the simulator, unlike the feedback in a vehicle where the ABS activation is occurring at the wheel, outside of the passenger compartment. Participants were also asked how hard it was to activate ABS or pass on the simulator compared to what they previously experienced in a vehicle. Eight (67%) of the participants thought the difficulty of activating ABS on the simulator was similar to what they experienced in a vehicle. One participant thought it was too hard to activate ABS or pass on the simulator, two participants thought it was a little harder to activate ABS or pass in the simulator, and one participant thought it was a little easier to activate ABS in the simulator compared to what they experienced in a vehicle.

9.2.2.4.3 Evaluation of How Pedals Emergency Stop© Prompts the User

Participants were asked if they thought the *Pedals Emergency Stop©* interactive exercise prompted them to press the brake hard enough to activate ABS or pass. Twenty (83%) participants thought the interactive exercise prompted them to press the brake hard to activate ABS or pass. Ten of the participants identified the audible “Stop” to be what prompted them to press the pedal hard, three of the participants relied on the feedback from the results page to understand how hard to press the pedal, two participants thought the target zone prompted them, and two participants said it took a few attempts for the interactive exercise to make sense. Two participants did not think the interactive exercise prompted them to press the brake pedal hard enough to activate ABS or pass. The remaining two participants did not identify if the interactive exercise prompted them to press the pedal hard, but one participant said they knew to press the pedal all the way down due to previous experience and the other participant had never activated ABS, needing time to figure out how hard to press.

Participants were asked if the location and the size of the target zone prompted them to press the brake pedal all the way down. Twenty-three (96%) participants reported that the location of the target zone prompted them to press the brake pedal all the way down. Only one participant did not think the location of the target zone prompted them because the target zone appeared in the expected location. Fifteen (63%) participants thought the size of the target zone prompted them to press the pedal all the way down and nine participants did not. Of the nine participants that did not think the size of the target zone prompted them to press the pedal all the way down, seven participants did not have any changes to the size of the target zone, the location was more important. Two of the participants wanted the size of the brake target zone and the gas target zone to match, either by making the gas target zone smaller or by making the brake target zone bigger.

During *Pedals Emergency Stop©* an audible "Stop" accompanied the presentation of the brake target zone, to help prompt participants to press the brake pedal hard. Participants were asked if the audible "Stop" helped prompt them to press the brake pedal hard, where 15 (63%) participants thought the audible "Stop" prompted them to press the brake hard, five participants did not think so, and four did not agree or disagree. Of the five participants that did not think the

“Stop” helped them to press the brake pedal hard, two participants wanted to hear a sound instead of a word, two wanted a realistic driving scene with an emergency braking scenario instead of a sound, and one participant did not want anything different, the audible “Stop” did not prompt them. Each of the four participants that did not agree or disagree, each participant had a different reason ranging from being startled, the “Stop” helped with reaction time but not to press hard, not hearing the “Stop” at all and the “Stop” helped if you were inattentive, but during the interactive exercise the participant was looking for the brake target zone to appear.

9.2.2.4.4 Suggestions to Improve the Pedals Emergency Stop© Interactive Exercise and Protocol

Participants were given a printed copy of the instructions for the *Pedals Emergency Stop*© interactive exercise and asked to provide suggestions. Fifteen participants did not have any suggestions, but seven participants provided suggestions. The most common suggestions were to add additional information about the brake target zone location and emphasize to brake as if in an emergency braking scenario. After gaining the consistent suggestion to include the location of the brake target zone, the last seven participants were asked if it would be beneficial to include the location of the brake target zone in the instructions. Three of the participants thought it would be helpful to include and three participants did not think including the location of the target zone would be helpful.

Participants read through the explanation of the ABS and feedback before being asked for suggestions to improve the explanation. Eighteen participants did not have any suggestions and the six remaining participants provided suggestions. Two participants identified small changes to make the instructions clearer by adding a word or changing the sentence structure. One participant wanted emphasis added that the explanation was focused on an emergency braking situation. Another participant suggested to add a sentence about how the feedback and noise from ABS is normal and expected. One participant that received the explanation of ABS after the first target of *Pedals Emergency Stop©* wanted the explanation before the interactive exercise. Lastly, one participant did not think it was fair to state that the driver could activate ABS because ABS activation in a vehicle is dependent on a variety of conditions.

After the suggestion to emphasize an emergency braking scenario, seven of the participants were asked if the description of how to press the brake pedal within the explanation of ABS and the feedback, matched their description. Four participants said the description of how to press the brake pedal is consistent with how they would describe it to someone else and three participants offered suggestions. One participant would add where you position your foot on the accelerator or brake affects your performance. One participant would emphasize hard braking and holding. The other participant suggested to highlight removing your foot from the brake and lifting it before stomping on the brake pedal.

As participants viewed an example of the results page from the *Pedals Emergency Stop©* interactive exercise, they were asked if they had any suggestions to improve the results page. Seven participants offered suggestions and 17 participants did not have any suggestions. Four participants suggested to change the “Slam brake” advice to be more descriptive, like move foot to brake as quickly as possible, hard braking or hard press, and press brake faster. Three participants wanted their reaction time for each attempt added.

After the suggestion to change the “Slam brake” advice, seven participants were asked if would be beneficial to change the advice to either press faster or press harder and faster. Four of the participants wanted the advice changed to press harder and faster. One participant wanted the advice changed to press harder. One participant thought it would be helpful to be more explicit with the advice, like to press faster or press harder. One participant wanted to keep the advice as "Slam brake".

Participants read through the explanation of the results page from the *Pedals Emergency Stop*© interactive exercise and were asked for their suggestions. Only four participants had suggestions, where two participants suggested to change the explanation if the advice changes, one participant wanted the description of when you did not pass to include not pressing fast enough, and one participant wanted advice on what you did correctly when you passed.

9.2.2.4.5 Hardest Part of Activating ABS or Receiving a Pass During the Pedals Emergency Stop© Interactive Exercise

After experiencing the *Pedals Emergency Stop*© interactive exercise, participants were asked what the hardest part of activating ABS or getting a pass was. Thirteen participants said the hardest part was how hard or the amount of force needed to stomp or slam the brake pedal. Four of the participants identified the short amount of time to press the brake as the hardest part. Three participants said there was not a hardest part. Two participants thought resisting the feedback from ABS while holding the brake pedal was most difficult. One participant found the lack of a steering wheel to cause difficulty pressing the brake pedal fast enough and another participant thought being aware of the "Stop" and moving their foot to the brake was most difficult.

9.2.2.4.6 Number of Attempts During the Pedals Emergency Stop© Interactive Exercise

During the study, each participant ran through *Pedals Emergency Stop*© three times for a total of 15 attempts. Participants were asked if they had enough attempts or if they wanted more.

Twenty-two (92%) participants thought they had enough attempts and two participants wanted more. The two participants wanted to run through *Pedals Emergency Stop©* one more time to have five more attempts.

9.2.2.4.7 Usability Statements

Participants were asked to respond to statements using a 1-5 scale, where 1 was strongly disagree and 5 is strongly agree. The results suggest that participants did not find the *Pedals Emergency Stop©* interactive exercise to be unnecessarily complex (*M* =1.46), the *Pedals Emergency Stop©* was found to be a practical tool (*M* =4.17) and many participants reported their understanding of ABS was improved (*M*=4.08). The average score when participants were asked if they felt as though they would practice using ABS in a vehicle was 2.71, where many participants neither agreed nor disagreed with the statement. The majority of participants would recommend the ABS practice task for new drivers (*M* =4.50), refresher training (*M* =4.38), and for evaluating fitness to drive (*M* =3.96). Table 30 summarizes the results of the adapted SUS.

Table 30. Results for the usability statements

Statement	Goal	Average	Min.	Max.	SD
I found the ABS practice task unnecessarily complex.	1	1.46	1	2	0.51
I found the ABS practice task to be a practical tool.	5	4.17	2	5	0.87
I think my understanding of ABS was improved from the ABS practice task.	5	4.08	3	5	0.78
I feel as though I will practice using ABS in a vehicle after using the ABS practice task.	5	2.71	1	5	1.08
I would recommend the ABS practice task for new drivers.	5	4.50	3	5	0.72

I would recommend the ABS practice task for refresher training.	5	4.38	3	5	0.77
I would recommend the ABS practice task for evaluating fitness to drive.	5	3.96	2	5	0.81

9.2.3 Discussion

The purpose of this usability study was to explore *Pedals Emergency Stop*©, an interactive exercise on driving simulator where users practice emergency braking and experience the haptic feedback associated with ABS activation. The usability study consisted of 24 participants ranging in age from 21 to 54 with an average age of 24.75. Participants were grouped by their prior experience feeling ABS activate and when they received the explanation of ABS. Half of the participants reported experiencing the feel of ABS activation before the study and half had no experience with ABS activation. Eleven participants received the explanation of ABS before the *Pedals Emergency Stop*© exercise and 13 participants received the explanation of ABS after the first attempt during the *Pedals Emergency Stop*© interactive exercise. Participants completed the *Pedals Emergency Stop*© exercise three times, totaling 15 attempts. After the simulator portion of the study, participants answered questions about the simulator and the *Pedals Emergency Stop*© interactive exercise in an interview format.

Over all attempts, on average, participants' performance increased dramatically over the first five attempts, from four participants receiving a pass on attempt one to 20 participants receiving a pass on attempt five. Performance varied slightly from attempts six through 15, ranging from 18 to 22 participants receiving a pass. The lowest performance from attempt six through 15, was during attempts six and 11, where 18 participants passed. The dip in performance during attempts six and 11 was mostly likely due to the break as the *Pedals*

Emergency Stop© interactive exercise was restarted. Twenty-two (92%) participants were able to receive a pass during the first five attempts of *Pedals Emergency Stop©*. One participant needed 14 attempts to gain a pass and one participant never passed. In total, 92% of the participants thought they had enough attempts, where two participants wanted to complete an additional trial of *Pedals Emergency Stop©*, to gain five more attempts.

The twelve participants that reported knowledge and experience feeling ABS activate prior to the study were asked to compare the ABS activation on the simulator to their previous experience in a vehicle. Fifty-eight percent of participants thought the feel and 50% thought the sound of ABS from the simulator felt similar to their previous experience. Sixty-seven percent of participants though the difficultly of receiving a pass or activating ABS on the simulator was similar to their previous experience.

All 24 participants were asked questions regarding how *Pedals Emergency Stop©* prompted their braking behavior. The consensus was that *Pedals Emergency Stop©* prompted participants to press the brake pedal hard enough and all the way down in order to pass. In fact, 83% of participants thought *Pedals Emergency Stop©* prompted them to press the brake pedal hard enough to pass, 96% of participants thought the location of the target zone prompted them to press the pedal all the way down and 63% of participants thought hearing “Stop” prompted them to press the brake hard enough to pass. Also, 88% of the participants thought the volume of the audible “Stop” was just right.

At the end of the interview portion of the study participants were asked to respond to the adapted SUS statements based on their level of agreement. The results show that participants did not think *Pedals Emergency Stop©* was not unnecessarily complex and participants’ understanding of ABS was improved from *Pedals Emergency Stop©*. *Pedals Emergency Stop©*

was also identified as a practical tool, recommended for new drivers, refresher training and evaluating fitness to drive.

The suggestions provided by the participants and observations from researchers identified several opportunities for improvements. The number of training sessions can be e reduced, specifically, the *Pedals Static©* and *Reaction Timer Stoplight©* interactive exercises will be removed from the protocol. The protocol for the next simulator study should include the short instruction used in the current study, where participants pressed each pedal five times, alternating between the gas and brake to feel the full range of each pedal. Then the short instructions will be followed by *Pedals Chase©* Level 2, to ensure that participants have the motor control to keep the indicator in the moving target zone, which is a portion of the *Pedals Emergency Stop©* interactive exercise.

One of the biggest realizations from the results of this study was the need to change the focus from ABS to emergency braking. Though very few participants identified that an emergency braking scenario should be emphasized during the study, emergency braking is the context to when ABS activates. *Pedals Emergency Stop©* is designed for participants to practice emergency braking, pressing the brake pedal as quickly as possible to slow the vehicle down and stop in the shortest distance possible. ABS often activates during emergency braking, requiring drivers to be prepared for it to activate, but that should not be the focus. Thus, the *Pedals Emergency Stop©* interactive exercise, often referred to as the ABS practice task throughout this study, should be called the emergency stop exercise. This refocus also requires changes to the explanation of ABS and the feedback. The focus of the explanation should be about emergency braking, with a portion on ABS. The beginning of the explanation should be changed to: *For this task, you will be practicing emergency braking. During 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 (ABS) to activate during emergency braking.*

One of the suggestions that came out of the evaluation of the explanation of ABS was to include information about the noise associated with ABS activation. The explanation of emergency braking, including the description of ABS should include information about the noise from ABS activation: *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.*

It was observed that some of the participants pivoted their foot from the gas to the brake pedal by rotating about the heel during *Pedals Emergency Stop*©. Some of the participants that pivoted between the pedals were able to pass, but participants that pivoted had more difficulty pressing the brake pedal fast and hard enough to receive a pass. Some of these participants even caught their right foot behind the brake pedal when trying to move from the gas to the brake pedal. All participants that pivoted were male and ranged in shoe size from US men's 9 to 13. These observations are consistent with Xi (2015), who found that drivers with shoe lengths over 29cm or larger than US men's 12, were more likely to pivot between the pedals. Xi (2015) also identified that lifting the foot to move between the pedals allowed for faster brake presses and drivers tended to use a lifting strategy over pivoting during an emergency braking scenario. This observation by Xi, may explain why some of the drivers that used the pivoting strategy struggled to pass and received the feedback to "Slam brake". With the added emphasis on emergency braking for future studies, information should be added to the emergency braking explanation to include the lifting strategy: *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 …*

The results for the suggestions to improve the instructions for *Pedals Emergency Stop©*, resulted in three participants suggesting adding the location of the brake target zone to the instructions. Based on the feedback from participants, seven participants were asked if the location of the brake target zone should be included in the instructions. Three participants wanted the location of the target zone included and three participants did not, who all had prior experience feeling ABS active and most likely knew where the target zone was going to appear. The instructions should include the location of the brake target zone in the instructions for *Pedals Emergency Stop©: When the brake pedal target appears at the top of the pedal on the screen and you hear "Stop", press the brake pedal all the way down as quickly as possible.*

Similarly, suggestions from four participants identified the advice from *Pedals Emergency Stop©* to "Slam brake" should be more descriptive. The four participants wanted the advice changed to statements like press harder, press faster or press as fast as possible. Based on this suggestion, seven participants were asked if the advice to "Slam brake" should be changed to press brake faster and harder, press brake faster, or something else. Four of the seven participants wanted the advice changed to press faster and harder. During the study it was observed that seven participants struggled to press the brake pedal fast enough to pass; the participants were pressing the brake pedal far enough but did not press the brake fast enough to pass. The participants may have interpreted pressing the pedal hard as how far the pedal was pressed, not how fast and far the brake pedal was pressed. The advice to "Slam brake" should be changed to "Press brake faster and harder".

The results from the adapted SUS showed that one statement did not yield positive results. The statement "I feel as though I will practice using ABS in a vehicle after using *Pedals Emergency Stop©*" received an average score of 2.71 out of five, indicating that participants neither agreed nor disagreed with the statement. After further consideration, some of the participants may have been confused by this statement. Participants could have interpreted this statement as practicing activating ABS in their vehicle on the roadway with traffic, which could be dangerous if there are other vehicles nearby. The statement should be clarified: *I feel as though it would be beneficial to practice using ABS in a vehicle in a parking lot or track after using Pedals Emergency Stop©.*

The results from phase this usability study identified multiple areas of improvement, but overall, the study showed positive attitudes towards the interactive exercise and participants' performance passing *Pedals Emergency Stop©* was encouraging. The majority of participants did not make many suggestions for *Pedals Emergency Stop©* or the protocol. Almost all participants were able to receive a pass during the first five attempts of *Pedals Emergency Stop©* and performance over the 15 attempts became consistent. The next study incorporated the identified improvements and investigated the effect of those changes.

9.3 Evaluation of an Emergency Braking Practice Task on a Driving Simulator

9.3.1 Study Aims

This study aimed to ensure the changes from the usability study worked as anticipated and investigated participant's performance during the emergency braking practice with the *Pedals Emergency Stop©* interactive exercise. The study investigated potential differences between drivers with and without prior ABS experience as well as when the description of the emergency braking with ABS is introduced. Lastly, this study aimed to define the number of attempts for a participant's performance to plateau to "pass" during the emergency braking practice with *Pedals Emergency Stop©*.

9.3.2 Research Questions and Hypotheses

In this study, two hypotheses were explored.

9.3.2.1 Research Question and Hypothesis 1

The first research question was: Do licensed drivers with previous knowledge and experience feeling ABS, “pass” sooner than those who do not? The corresponding hypothesis was: Licensed drivers with previous knowledge and experience feeling ABS, “pass” in fewer attempts than those who do not. This result was expected due to the higher ratings from drivers with previous knowledge and experience feeling ABS activate on the track (Mims et al., 2021).

9.3.2.2 Research Question Hypothesis 2

The second research question was: Does hearing and reading the description of emergency braking using ABS matter if it is explained before or after a participant’s first attempt using the *Pedals Emergency Stop*© interactive exercise? The corresponding hypotheses was: Licensed drivers that receive the description of emergency braking prior to completing the *Pedals Emergency Stop*© interactive exercise will “pass” sooner than those who receive the description after their first attempt of the *Pedals Emergency Stop*© interactive exercise. This result was expected because the participants that receive the description of emergency braking have an increased understanding of the braking behavior needed to “pass” the exercise compared to drivers that receive the explanation after the first attempt of the *Pedals Emergency Stop*© interactive exercise.

9.3.2 Methods

9.3.2.1 Participants

Sixty-three participants were recruited to participate in the study. Two participants were dropped because they used their left foot to brake, unlike the other participants that used their right foot to brake. All participants had a driver's license (US or international for operation of a passenger vehicle). Participants consisted of 30 males, 31 females, and ranged from 18 to 60 years of age with an average age of 35.8 years (SD=11.6 years). Participants were grouped by their prior knowledge and experience using ABS where participants were screened for using ABS and were able to describe the haptic feedback associated with ABS activation, they were assigned to the prior ABS experience group. Participants who did not have experience previously activating ABS or who had an inaccurate description of the haptic feedback associated with ABS were assigned into the without knowledge and experience activating ABS group. Then, participants were grouped again by when they received the description of emergency braking, where half received the description before *Pedals Emergency Stop*© and half of the participants received the description after their first attempt of *Pedals Emergency Stop*©. Therefore, there were four groups with 15 or 16 participants each (see Table 31). There were more females with no knowledge and experience feeling ABS and more males who had knowledge and experience feeling ABS.

Table 31. Participant groupings based on prior ABS experience and order of the explanation of emergency braking during the Pedals Emergency Stop© interactive exercise

ABS grouping	**Order of description of emergency braking during *Pedals Emergency Stop*©**	
	Before	**After the first attempt**
No prior knowledge and experience feeling ABS	16 participants 4 males, 12 females Avg. age 35.0 (SD =10.0)	15 participants* 5 males, 10 females Avg. age 35.8 (SD =11.6)

Has prior knowledge and experience feeling ABS	15 participants 10 males, 5 females Avg. age 37.8 (SD =12.5)	15 participants 11 males, 4 females Avg. age 34.6 (SD =13.2)

* Within this group there were two participants that 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.

An analysis in GPower was conducted to determine that a minimum of 52 participants were needed to perform an analysis of variance to investigate main effects and interactions between ABS experience groups and protocol groups. The analysis was based on a large effect size (0.4) and power value of 0.8.

9.3.1.2 Materials

The study utilized the ABS simulator described in the usability study. The interactive exercises included *Pedals Chase©* and *Pedals Emergency Stop©* (see section 9.2.1.3 Interactive Exercises for a detailed description).

9.3.1.3 Procedure

During the study session, participants were first asked questions to ensure they met the inclusion criteria of being between 18 and 60 years old as well as having a driver’s license. Next, participants read the consent form and provided their consent. 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).

Participants then moved to the simulator and adjusted themselves to a comfortable distance from the pedals. Participants completed a short familiarization process, where they pressed each pedal to maximum travel five times, alternating between the gas and brake pedal to feel the full range of each pedal. Participants completed *Pedals Chase©* Level 2 with no more than three errors (Brooks et al., 2016) 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 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 participants completed the first attempt of *Pedals Emergency Stop©*. Then the other half of the participants heard and read the description of emergency braking after the first attempt. Then, all 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 didn’t press the brake pedal fast and hard enough or didn’t 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 get the advice to press brake faster and harder. If you do not hold the indicator in the target zone for 3 tones, you will get the advice to hold longer.” 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 trials.

After completing *Pedals Emergency Stop*©, participants completed a survey. The survey included questions regarding demographic information, but primarily, the survey consisted of questions to investigate the participants’ view on the number of attempts needed, as well as one adapted statement from the SUS. Participants were asked if they had enough trials during the emergency braking practice. For those who did report having enough practice, they were asked how many attempts they needed to feel confident with the task. For participants who did not think they had enough practice, they were asked how much more practice they would like to have. Next, all participants were asked to identify the hardest part of the emergency braking practice. For the statements (see Table 32), participants responded using a five-point Likert scale ranging from strongly agree (rating of 1) to strongly disagree (rating of 5). One statement from the SUS was modified. Additional statements relevant to the task were added. Lastly, participants were asked if they had any suggestions or additional comments about the study.

Table 32. Statements participants responded using a 1-5 scale, where a rating of 1 is strongly agree and a rating of 5 is strongly disagree

Question	Response type
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

The italicized statement was adapted from the original SUS.

9.3.1.4 Data Organization and Analysis

The data from *Pedals Emergency Stop©* and the surveys were combined and organized by participant. To investigate the research questions and hypotheses, 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 variables were the prior ABS experience (two levels) and when the description of emergency braking with ABS occurred (two levels). The ANOVA determined if there was a main effect of ABS experience to determine if prior ABS experience effected the number of attempts it took a participant to "pass", which addressed research question and hypothesis 1. The other main effect investigated determined if there were differences in the number attempts to receive a "pass" based upon when the participant received the description of emergency braking, which addressed research question and hypothesis 2. The ANOVA tested for an interaction between the two grouping factors, which determined if there was a relationship between participants prior ABS experience and when they received the description of emergency braking.

To determine the number of attempts that were needed for performance to plateau with a “pass”, a survival regression using the Cox Proportional Hazard Model was conducted. Survival regressions examine effects of predictor variables on the amount of time to an event (Fisher & Lin, 1999). Unlike other regression models, survival regressions contain a time component. For this study, the number of attempts was treated as the time interval and when the participants earned a “pass” was the dependent variable. The regression determined if the predictors of prior ABS experience and/or when the participant received the description of emergency braking had an effect on their ABS performance plateauing.

9.3.3 Results

9.3.3.1 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 through 15, the percentage of participants that passed became more consistent, varying between 69% to 84% (see Figure 70).

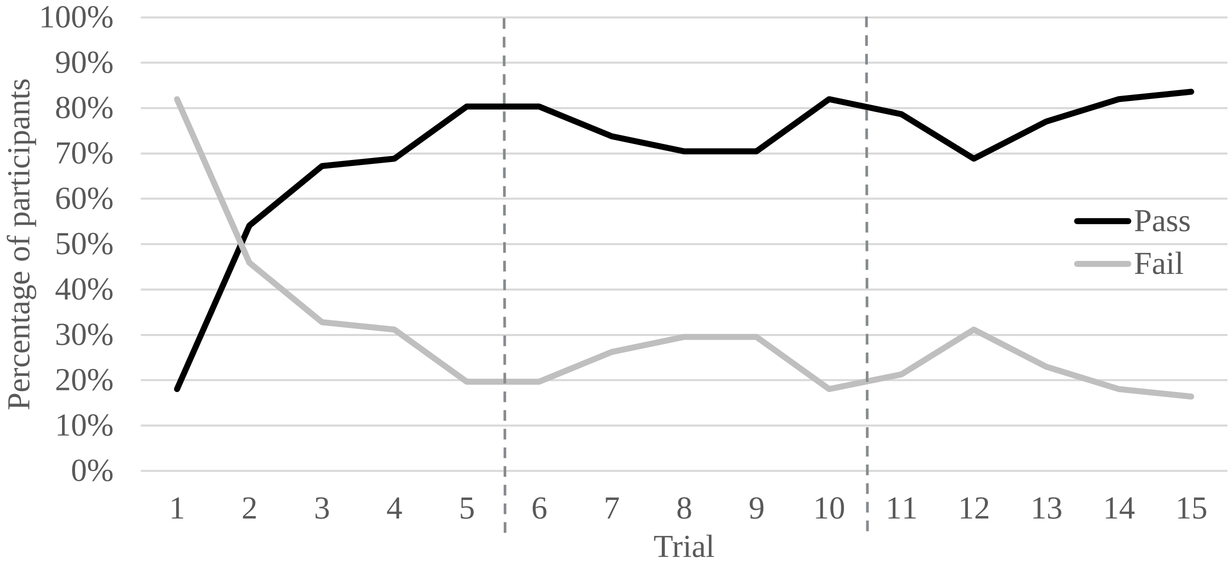


Figure 70. Percentage of participants to pass and fail on each trial.

Note: Dotted vertical lines designate the breaks when restarting Pedals Emergency Stop©

A Chi-square tests was conducted to investigate differences in the number of participants that pass and fail between all 15 trials. The results of the Chi-square test indicated a significant difference between the number of participants that pass and fail 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 being made 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 other trials (see Table 33). 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 33).

Table 33. 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. While the participants were grouped based on whether they had or did not have previous knowledge and experience with ABS as well as 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.

9.3.3.2.1 Performance Passing by Group Over All Trials

The participants were grouped based on whether they had or did not have previous knowledge and experience with ABS as well as the order in which they received the description of emergency braking (for a total of four groups). Each of the four group's performance is described. For the first trial, the group which consisted of the participants with prior knowledge and experience with ABS that received the description of ABS prior to the *Pedals Emergency Stop*© interactive exercise had the highest percentage of participants pass, with 40%. Only 13% of participants in who received the description of emergency braking after the first trial both the group with prior and the group without prior ABS experience passed on the first trial. The group with the poorest passing percentage for the first trial at 6% were the participants without prior ABS experience that received the description of emergency braking prior to the *Pedals Emergency Stop*© interactive exercise. Interestingly, by trial three, the percentage of participants to pass rose above 50% for all four groups. By trail give, all four groups had 70% or above passing. From trials five through 15, the percentage of participants to pass became more consistent, ranging between 60 and 93% (see Figure 71).

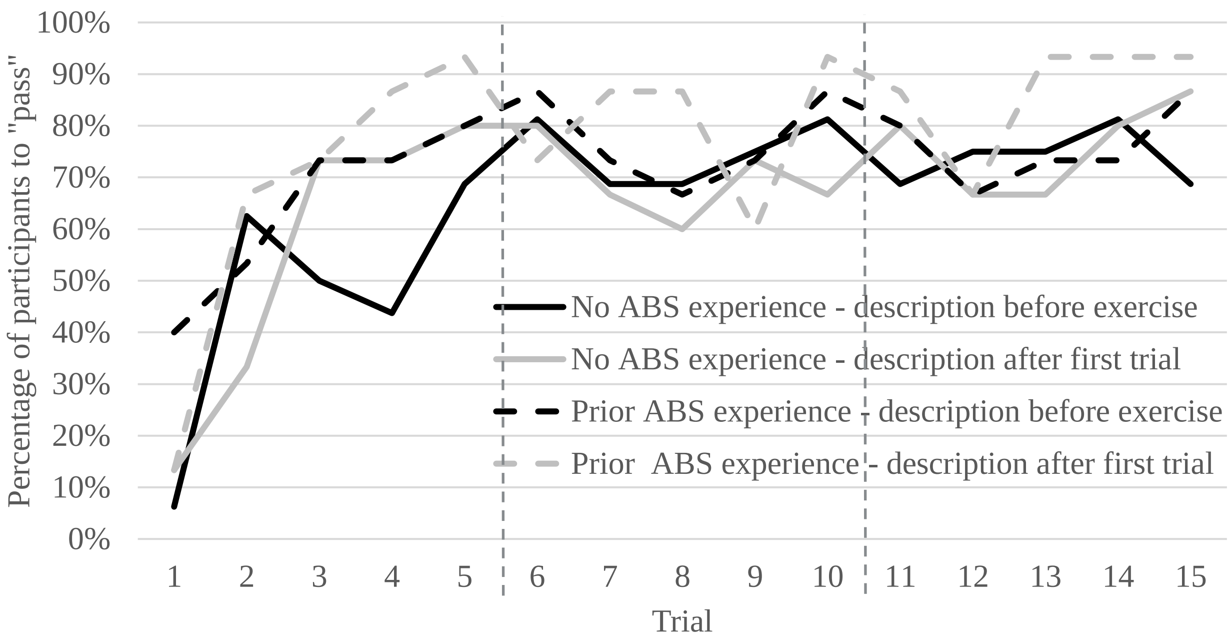


Figure 71. Percentage of participants to pass on each trial by group.

Note: Dotted vertical lines designate the breaks when restarting Pedals Emergency Stop©

For participants who did not have prior knowledge and experience feeling ABS, those in the group that received the description of emergency braking before the *Pedals Emergency Stop*© interactive exercise “passed” an average of 9.8 trials out of the 15 trials (*SD*=3.9, *Min*=2, *Max*=14), and the group that received the description of emergency braking after the first trial “passed” an average of 10.0 trials out of the 15 trials (*SD*=3.9, *Min*=2, *Max*=14). Participants with prior knowledge and experience feeling ABS in the group that received the description of emergency braking before the *Pedals Emergency Stop*© interactive exercise “passed” an average of 10.9 trials out of the 15 trials (*SD*=4.3, *Min*=2, *Max*=15), and the group that received the description of emergency braking after the first trial “passed” an average of 11.7 trials out of 15 trials (*SD*=2.6, *Min*=4, *Max*=14). An exploratory ANOVA was conducted to determine if there were significant differences in the average number of “passes” across all the trials based upon prior ABS experience and/or the order of the description of emergency braking. The results of the ANOVA did not reveal any significant differences or interactions between the groups.

9.3.3.2 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 3 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 72).

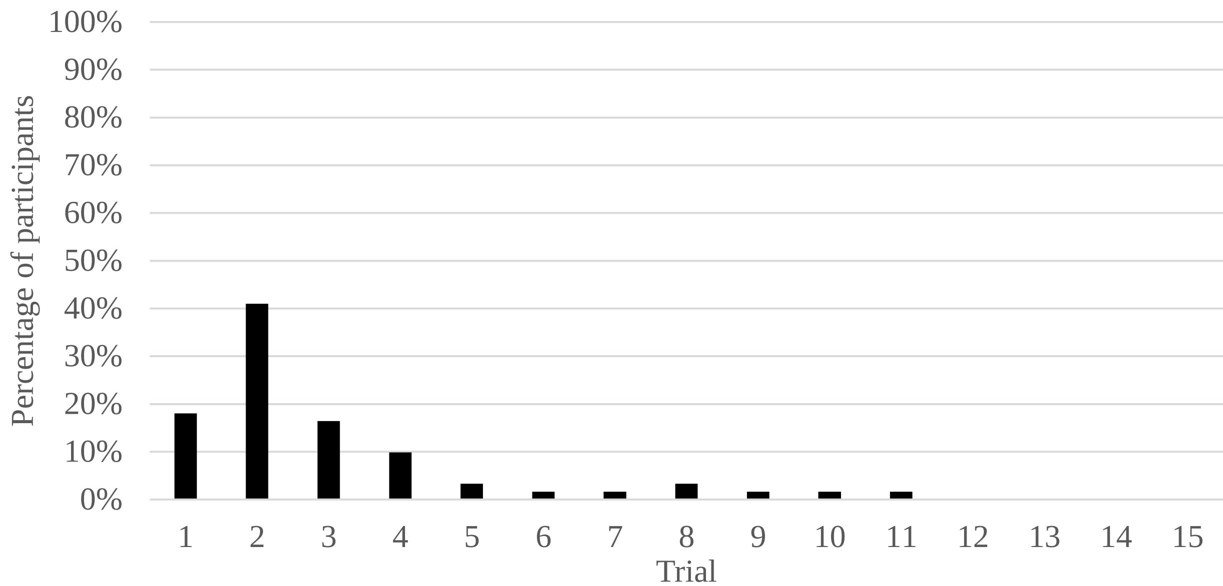


Figure 72. Participants first pass by trial

Performance was evaluated based upon the participants' group based on their previous knowledge and experience feeling ABS activate as well as by when they received the description of emergency braking during the *Pedals Emergency Stop©* interactive exercise, but there were no significant differences found between the groups.

9.3.3.2.1 Number of Trials to Pass for the First Time by Group

Performance was evaluated based upon the participants' group based on their previous knowledge and experience feeling ABS activate as well as by when they received the description of emergency braking during the *Pedals Emergency Stop©* interactive exercise. The participants who had knowledge and experience feeling ABS prior to the study took fewer trials to pass compared to the participants without knowledge and experience feeling ABS (see Figure 73). For participants who had experienced ABS, those who had the description of emergency braking prior to the *Pedals Emergency Stop©* interactive exercise "passed" in an average of 2.60 trials

(*SD*=2.20, *Min*=1, *Max*=9), which was similar to the 2.67 average trials to “pass” (*SD*=1.72, *Min*=1, *Max*=8) for the participants that received the description of emergency braking after their first attempt. For the participants without prior knowledge or experience feeling ABS, participants that had the description of emergency braking before the interactive exercise “passed” in an average of 3.31 trials (*SD*=2.44, *Min*=1, *Max*=10) while those who received the description after their first attempt “passed” in an average of 3.47 trials (*SD*=2.67, *Min*=1, *Max*=11).

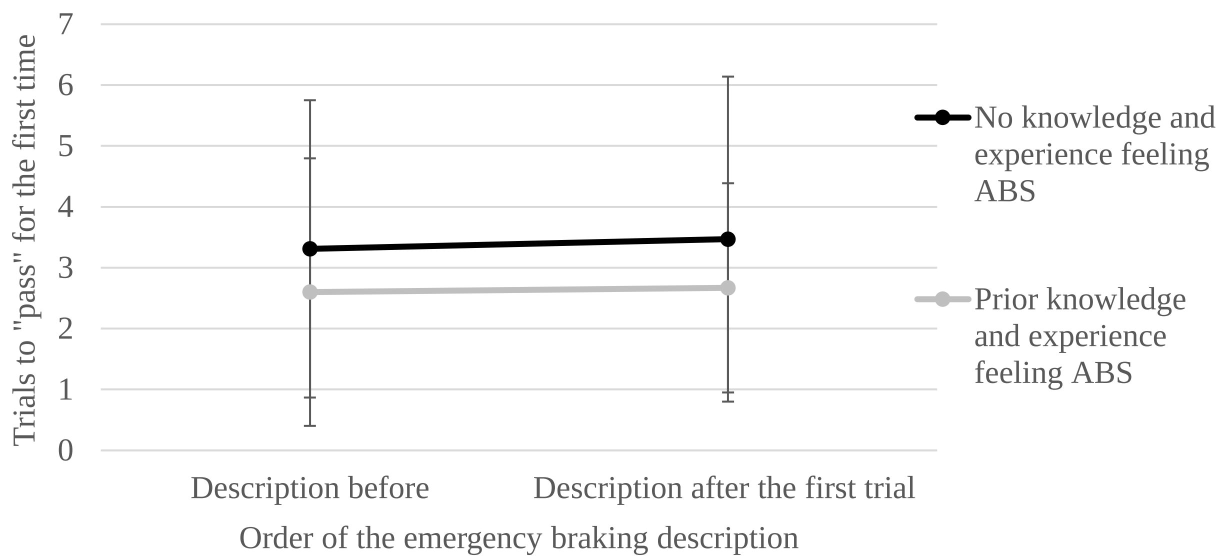


Figure 73. Average trials to pass by group

To determine if there were any statistical differences between the number of trials to “pass” based on participant’s knowledge and experience with ABS as well as the order in which they received the description of emergency braking, an analysis of variance (ANOVA) was performed. In order to correct for skewness and kurtosis, a log transformation was used, though the normality assumption was not restored. There were no significant effects found from the ANOVA, concluding there was no main effect for the participants’ prior knowledge of and experience with ABS nor the order the description of emergency braking was received. There was also no interaction between the participants' prior knowledge of and experience with ABS and the order the description of emergency braking. Then, an exploratory analysis using a Poisson regression was completed to verify that prior ABS experience and order of the description of emergency braking were not predictors of when a participant received their first "pass". The results of the Poisson regression showed that neither prior ABS experience nor the order of the description of emergency braking were found to be predictors of the number of trials to "pass". An additional exploratory analysis was conducted to determine if there were differences in the variability associated with the number of trials to "pass". In addition, a Chi-Square test revealed no statistically significant differences in variability with the number of trials to "pass" between the groups.

To determine if the predictors of ABS experience and when the participant received the description of emergency braking had an effect on the number of attempts needed for performance to plateau with a "pass", a survival regression using the Cox Proportional Hazard Model was conducted. The number of attempts (15) was treated as the time interval and when participants "passed" served as the dependent variable. The regression was not found to be significant, thus neither predictor had any influence on performance plateauing.

9.3.3.3 Exercise Feedback (Advice)

When 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. 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 the participant 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, 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).

9.3.3.4 Survey Results

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

9.3.3.4.1 Amount of Practice

Participants were asked if they thought they had enough emergency braking attempts on the simulator. The majority (91.8%) of participants thought they had enough practice and only 6.5% of the participants did not think they had enough practice. One participant responded "maybe" they had enough practice. For the participants that thought they had enough practice, 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 practice, they were asked how many more attempts they wanted to have, responses included two, five, 20 and 30 more attempts.

9.3.3.4.2 Hardest Part of the Pedals Emergency Stop© Interactive Exercise

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”.

9.3.3.4.3 Usability Statements

Participants were asked to respond to statements using a 1-5 scale, where 1 was strongly disagree and 5 is strongly agree. The results suggest that 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), participants thought 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 participants recommend the ABS practice 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 practice task for evaluating fitness to drive (*M*=3.88). See Table 34 for a summary of the results.

Table 34. 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

9.3.4 Discussion

The goal of this study was to evaluate a novel emergency braking practice using a simulator and the *Pedals Emergency Stop*© interactive exercise. The simulator provided haptic brake pedal feedback consistent with ABS activation. The *Pedals Emergency Stop*© interactive exercise prompts individuals to practice emergency braking with 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, then a stationary brake pedal target appears at the very top of the brake pedal at the same time a “Stop” prompt is played. 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, 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”. A total of 61 participants completed this study, ranging from 18 to 60 years of age. Participants were in one of four groups based upon their knowledge of and experience feeling ABS prior to the study as well as when they heard and read the description of emergency braking with ABS either prior to completing the *Pedals Emergency Stop*© interactive exercise or after their first attempt of the interactive exercise. In total, participants completed 15 emergency braking attempts.

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 4 trials of the 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 their 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 the simulator practice was a practical tool.

9.3.4.1 Discussion of Research Question and Hypothesis 1

The first research question was: Do licensed drivers with previous knowledge and experience feeling ABS, “pass” sooner than those who do not? The corresponding hypothesis was: Licensed drivers with previous knowledge and experience feeling ABS, “pass” in fewer attempts than those who do not. This result was expected due to the higher ratings from drivers with previous knowledge and experience feeling ABS activate on the track in an earlier study of this dissertation (Mims et al., 2021). The results of the ANOVA revelated that there was no main effect of ABS experience, thus drivers with previous knowledge and experience feeling ABS did not “pass” any sooner than those without knowledge and experience with ABS. These results suggest the ability to receive a “pass” during the *Pedals Emergency Stop©* interactive exercise is not dependent on a driver’s previous knowledge of or experience with ABS. This finding suggests the *Pedals Emergency Stop©* interactive exercise is easy to understand and use regardless of prior experience with ABS.

9.3.4.2 Discussion of Research Question and Hypothesis 2

The second research question was: Does hearing and reading the description of emergency braking using ABS matter if it is explained before or after a participant’s first attempt using the *Pedals Emergency Stop©* interactive exercise? The corresponding hypotheses was: Licensed drivers that receive the description of emergency braking prior to completing the *Pedals Emergency Stop©* interactive exercise will “pass” sooner than those who receive the description after their first attempt of the *Pedals Emergency Stop©* interactive exercise. This result was expected because the participants that receive the description of emergency braking have an increased understanding of the braking behavior needed to “pass” the exercise compared to drivers that receive the explanation after the first attempt of the *Pedals Emergency Stop©* interactive exercise. The results of the ANOVA revelated that there was no main effect on the order when the description was provided. Drivers that heard and read the description of emergency braking prior to completing the *Pedals Emergency Stop*© interactive exercise did not "pass" any sooner than those who received the description after their first attempt.

9.3.4.3 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". Though the majority of participants were able to "pass" for the first time within the first four trials, it took participants four to five trials before 70-80% of 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. 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 it takes a driver to turn the wheel in 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 81 for an example of the results for *Reaction Timer Stoplight©* where the task is displayed in the center.

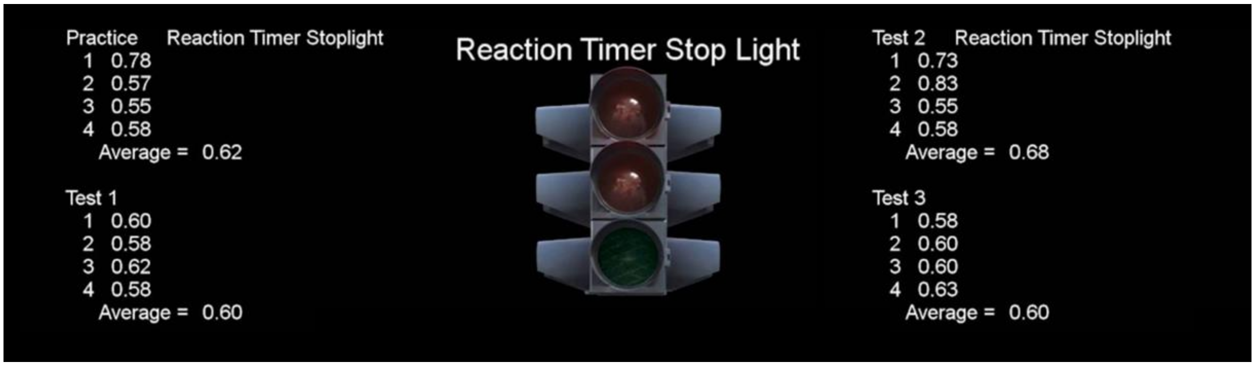


Figure 74. Results screen for Reaction Timer Stoplight©

Second, since 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 75).

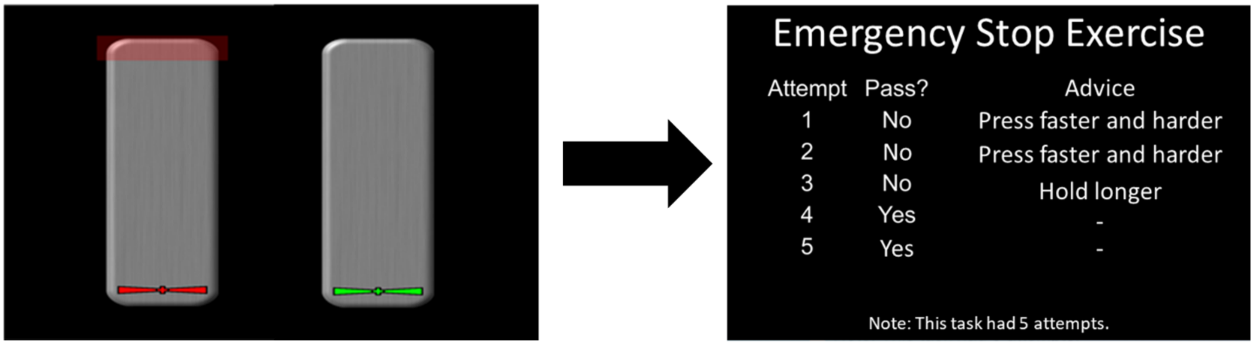


Figure 75. Current Pedals Emergency Stop© interactive exercise, which rotates between the task screen with the pedals and the results screen

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. The purposed changes could look like **Error! Reference source not found.**, where the task is in the center of the screen and the results populate on the outer edges of the screen.

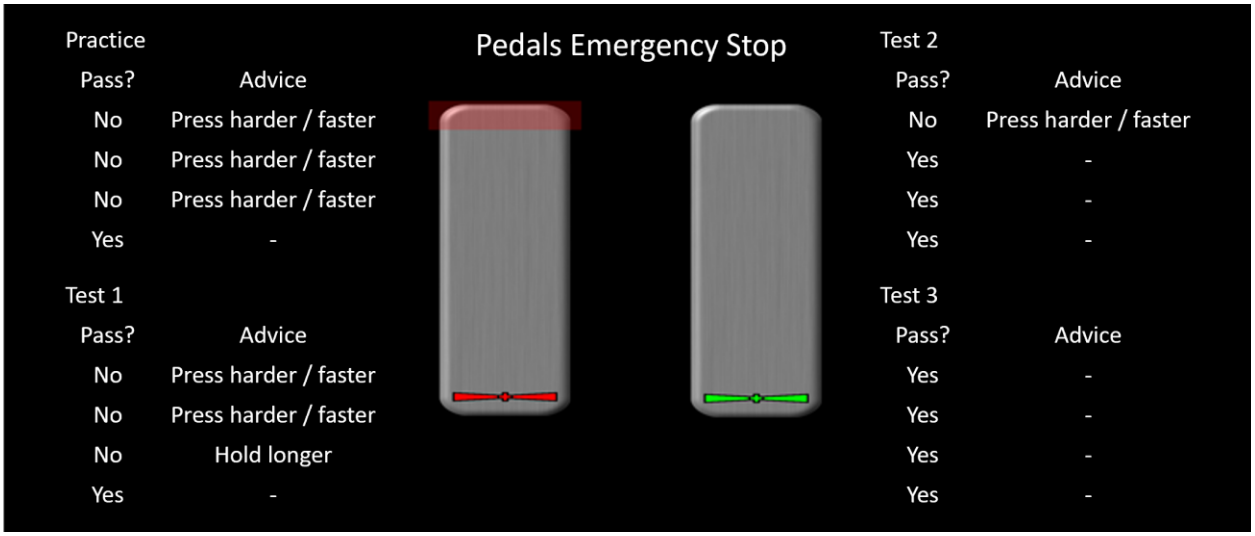


Figure 76. Example of the proposed Pedals Emergency Stop© combined task and results layout

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 practice and felt confident after 6 trials. Participants "passed" an average of 3 trials prior to reporting feeling confident. Based on these results from the survey, reasonable criteria 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 77). Note that since participants in the current study completed 15 trials instead of the proposed 16 trails, test 3 is in the current study is one trial short and only contains three trials.

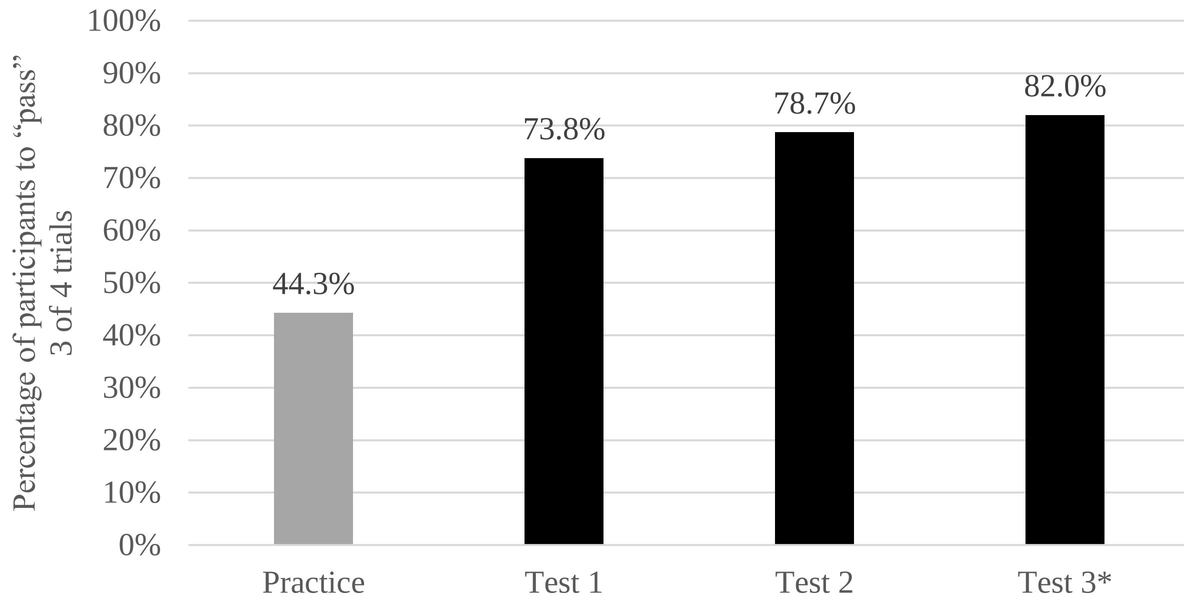


*Figure 77. Percentage of participants to pass with the trials regrouped into sets of four with a practice, test 1, test 2 and test 3. *Test 3 only consisted of three trials because participants in the current study completed 15 trials. Eight percent of participants passed two of the three trials in test 3, who may have passed test 3 with the fourth trial.*

9.3.5 Conclusions

The overarching goal of this study was to evaluate a novel emergency braking practice 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 repeated practice 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. Participants had 15 trials to practice emergency braking with ABS. 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 participants in this study received a "pass" a minimum of two times during the practice. 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 practice, that the practice was a practical tool, and recommended the training for new drivers, refresher training, as well as evaluating fitness to drive. The results of this study suggest that the emergency braking practice using the *Pedals Emergency Stop*© interactive exercise can be an effective tool for drivers to practice emergency braking with haptic ABS feedback.

9.3.6 Limitations

The simulator utilizes a high end set of pedals for video game use. The feel and pedal 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 is the sound is coming 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.

9.3.7 Future research

Future studies should explore the proposed grouping of a practice with three tests consisting of four trials as well as the criteria of “passing” three out of four trials to “pass” one of the tests. The results of the survey showed that the emergency braking practice is recommend 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 at-risk driving populations. Future research should investigate how the emergency braking practice on the simulator generalizes to on-road driving.

9.3.8 Practical Applications

The results of this study suggest that the emergency braking practice on the simulator may be a practical tool, regardless of an individual’s previous knowledge and experience with ABS. Chapter Ten aims to explore how the emergency braking practice on the simulator generalizes to on-road driving for individuals with and without prior experience activating ABS.

CHAPTER TEN: STUDY VIII – INVESTIGATION OF THE EFFECT OF AN EMERGENCY BRAKING PRACTICE ON A DRIVING SIMULATOR WITH HAPTIC ANTI-LOCK BRAKING SYSTEM FEEDBACK ON BRAKING PERFORMANCE ON A TRACK

10.1 Introduction

One of the primary causes of fatalities and injuries around the world are traffic crashes (WHO, 2020). In the US, the majority of crashes are due to driver error (94%; Singh, 2018). To address driver error, safety systems in vehicle technology aim to assist drivers to help mitigate or prevent crashes. One example is braking systems, where brakes assist drivers in emergency situations in addition to their primary purpose of stopping the vehicle.

10.1.1 Anti-lock Braking System (ABS) Overview

The anti-lock braking system (ABS) was developed to assist drivers in emergency braking situations by preventing skidding or loss of control caused by locked wheels (Duffy, 2009). A locked wheel cannot rotate, thus is skidding across the road surface and will not respond to steering input from the driver. Conventional brakes (pre-ABS) required the driver to "pump", rapidly press and release brake pressure, in an emergency. The required "pumping" was frequently difficult for drivers to achieve and if performed incorrectly could cause the vehicle's brakes to lock. ABS was created to automate the "pumping" action, requiring the driver to simply depress the brake pedal. The modulation of brake pressure by ABS created a vibration or "thumping" in the pedal that the driver experienced. The intention of ABS was to prevent skidding and loss of control due to locked wheels and allow the driver to retain control of the vehicle in emergency braking situations (Kahane, 1994).

The National Highway Traffic Safety Administration (NHTSA) compared crash records of vehicles with ABS and conventional vehicles without ABS to see if ABS had any effects on crash rates. As expected, NHTSA's initial report showed a reduction in fatal multi-vehicle crashes on wet roads, but there was an unexpected, significant increase in the number of fatal single vehicle run-off road crashes. Due to the observed increase in fatal crashes, ABS was not required as standard safety equipment (Kahane, 1994). To investigate the increase in crashes, NHTSA launched the Light Vehicle ABS Research Program (Garrott & Mazzae, 1999). The Light Vehicle ABS Research Program discovered that drivers did not understand the purpose of ABS, did not know when ABS was functioning, or if their vehicle was even equipped with ABS (Mazzae, Garrott & Snyder, 2001), but researchers were not able to identify any specific cause of the increase in crashes. The functionality of ABS became standard safety equipment in 2012 on all new passenger vehicles in the US as a component of electronic stability control (ESC [NHTSA, 2007]). Though ESC showed decreases in single vehicle crashes (Kahane, 2014), a disproportionately high number of rear-end crashes still exist. There were over two million rear-end crashes in the US in 2015, accounting for 33.4% of all crashes (NHTSA, 2017b). Similar to the findings from NHTSA's Light Vehicle ABS Research Program (Garrot & Mazzae, 1999), previous research by Mims et al. (2020a, 2020b, 2020c) suggests that teen and adult drivers do not have an understanding or experience with ABS and practice activating ABS may be an essential skill.

Understanding that not all drivers may have knowledge and experience with ABS, Mims et al. (2021) investigated how a driver's knowledge and experience with ABS effected performance braking in a vehicle. Adult drivers participating in a performance driving center's car control class focused on defensive driving skills completed a survey prior to the class to understand each participant's knowledge of and experience activating ABS. During the class, participants learned what ABS is and when it functions before activating ABS in a vehicle on a closed-road track. On the track, participants' ability to activate ABS was evaluated by the driving instructor using a behaviorally anchored rating scale. The scale consisted of five levels of ABS activation, which ranged from no activation (rating of 1) to full ABS activation throughout the entire stop (rating of 5; Table 35).

Table 35. Behaviorally anchored rating scale to rate performance activating ABS

Rating	Level of activation	Driver action
1	**None**	Does not press the brake pedal hard enough to lock the wheels, thus not activating ABS
2	**Brief**	Presses the brake pedal hard enough to lock the wheels and activate ABS momentarily, the pedal pressure is not consistent or enough to sustain ABS
3	**Some (three common scenarios)**	A. Slams on the brake pedal to activate ABS then **releases the brake pedal's pressure**, so ABS is no longer activated through the remainder of the stop
		B. **Eases onto pressing the brake pedal**, but not initially pressing hard enough to activate ABS, steadily applies enough brake pedal pressure to eventually activate ABS and sustain ABS through the rest of the stop
		C. Combination of both scenarios A. & B. where eases onto the brake pedal and releases the pedal at the end of the stop
4	**Most (two common scenarios)**	A. **Releases the pressure from the brake pedal** at the very end of the stop
		B. **Eases onto the brake pedal** at the very beginning of the stop
5	**Full**	Slams on the brake pedal and holds the pressure on the brake pedal until the vehicle comes to a complete stop

The results of the study indicated that drivers who understood the feel of ABS when activated, participated in additional driver's training beyond driver's education either with or without ABS experience, or those who practiced activating ABS, performed significantly better on their first of multiple ABS braking attempts compared to participants who only knew what ABS stood for, or those who reported experiencing ABS. 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 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 results suggested that training or practice using ABS may increase the likelihood of a drivers’ ability to fully activate ABS in emergency situations.

10.1.2 Training Methods for Emergency Braking

Few studies have investigated methods of ABS training, but there is limited literature on the use of driving simulator-based training for emergency braking practice with ABS. One publication that describes a driving simulator with ABS haptic brake pedal feedback is Task 5.1 of NHTSA’s Light Vehicle ABS Program, which utilized the National Advanced Driving Simulator (NADS; McGhee, 2000). Task 5.1 investigated crash avoidance behavior using NADS, which included a 190-degree forward and 60-degree rear field-of-view, with six-degrees-of-freedom base and fully instrumented 1993 Saturn LS2 vehicle (McGhee, 2000). NADS was retrofitted with ABS and relied on a full vehicle dynamics model from a Ford Taurus. The purpose of the simulator was to explore collision avoidance behaviors of drivers, rather than ABS training.

Chapter 9 describes how the previous study explored using a small footprint driving simulator with haptic brake pedal feedback and an interactive exercise for emergency braking practice. The study investigated if the emergency braking practice provided participants with the needed feedback to properly complete an emergency braking task engaging ABS and determined if there were differences in performance based on participants' prior knowledge and experience feeling ABS activate. The emergency braking practice utilized the *Pedals Emergency Stop©* interactive exercise, which used images of a gas and brake pedal with colored target zones. The interactive exercise began with a green moving gas pedal target that oscillated vertically on the gas pedal, followed by a stationary red brake pedal target that appeared at the very top of the brake pedal at the same time the participant heard “STOP”. Drivers were instructed to press the brake pedal as quickly as possible, moving the brake indicator into the target zone, and to hold the indicator in the target zone for three tones. When the driver pressed the brake pedal hard and fast enough into the brake target zone, they received the haptic ABS feedback instantly, but if a driver did not press the brake pedal hard and fast enough into the target zone, the haptic ABS feedback was delayed by one second. Drivers were then given feedback on their performance by indicating if they passed or not, where to “pass”, the driver had to press the brake pedal fast and hard enough as well as hold the brake indicator in the target zone for three tones, which corresponded to a rating of 5, indicating a full ABS stop where the driver slammed on the brake pedal from the beginning of the stop and held the brake pedal at the maximum travel until the vehicle came to a complete stop (see Table 35). If the driver did not “pass”, advice to improve their performance was presented on the screen, either to “press harder and faster” or to “hold longer” which corresponded to ratings related to no ABS activation (rating of 1) or ABS activation through a portion, but not the entire stop (ratings 2-4; see Table 35). Sixty-one participants completed the emergency braking practice on the simulator, where 30 of the participants had prior knowledge and experience feeling ABS activate and 31 participants did not. All participants completed the *Pedals Emergency Stop©* interactive exercise three times for a total of 15 trials. The results of the study showed that participants took an average of three trials to "pass" for the first time and 85% of the participants "passed" within the first four attempts. Performance "passing" significantly increased over the first two trials and became consistent over the remaining 13 trials, where there were no significant differences in the number of participants that "passed" over trials 3 through 15. There were no statistically significant differences between the participants that had previous knowledge and experience feeling ABS activate and participants that did not have knowledge or experience with ABS, suggesting performance during the simulator practice was not dependent upon prior knowledge and experience with ABS. The majority (91.8%) of the participants felt they had enough practice, where the average number of trials to feel confident "passing" was 5.6 trials and participants "passed" an average of 2.7 trials before the trial number they reported feeling confident "passing". Since 85% of all participants were able to "pass" within the first four trials, the *Pedals Emergency Stop©* interactive exercise was restructured to have sets of four trials per set instead of the original five trials per set where each set began with a practice with four trials, followed by three separate tests, each with four trials per test. Since the average number of trials "passed" prior to the participant feeling confident was 2.7, the criteria to then "pass" the interactive exercise will be to "pass" three out of four trials within a test.

Interestingly, there were different conclusions found by Mims et al. (2021; Chapter 7), where there were significant differences in a drivers' ability to activate ABS in a vehicle on a track based on the drivers' previous knowledge and experience feeling ABS activate, but there were no differences based on prior knowledge and experience feeling ABS activate observed during the emergency braking practice on the simulator (Chapter 9). The lack of differences between participants with and without prior knowledge and experience feeling ABS activate could be due to the nature of using a novel simulator, where all participants needed three or four trials to learn how to "pass". The simplicity of the *Pedals Emergency Stop©* interactive exercise, where participants visually monitor their gas and brake pedal positions coupled with the easy-to-understand feedback, could contribute to the lack of performance differences between participants with and without prior experience feeling ABS activate. For the on-track exercise described by Mims et al. (2021; Chapter 7), participants made emergency braking stops in a vehicle. The participants part of the track study were given an overview of ABS in a classroom and watched the professional driving instructor demonstrate emergency braking with ABS but it is known from previous research that simply hearing information about ABS or watching an ABS stop does not impact crash avoidance behavior (Mazzae et al., 2003). Participants who had previously activated ABS and understood the haptic feedback could rely on their past experiences, which may have caused the significant difference in performance observed during the track study (Mims et al., 2021).

10.1.3 Study Aims

This study's aims were to determine if the *Pedals Emergency Stop©* interactive exercise which was designed to train and assess emergency braking practice, impacts driver's ability to fully activate ABS on a track. Another goal of this research was to determine if there were differences between drivers with and without prior knowledge and experience activating ABS. Lastly, the study aims to address the improvements to the *Pedals Emergency Stop©* interactive exercise identified in Ch. 9 including the passing criteria.

10.2 Methods

10.2.1 Participants

Participants were recruited from a local manufacturing facility. Participants were between the ages of 18 and 60 years of age, have a driver's license, and operate the brake pedal with their right foot. Additional exclusion criteria included the use of adaptive equipment (hand controls, left foot gas pedal, etc.) and/or previous participation in driving courses beyond drivers' education (car control classes, advanced driving classes, driving classes for employees, etc.). Eighty potential participants were screened over the phone and scheduled for the study. The participants were assigned to groups during the phone screening based upon their previous knowledge and experience with ABS (no knowledge and/or experience feeling ABS vs. knowledge and experience feeling ABS). Then, those two groups were split into two ABS simulator practice groups (practice vs. no practice/control) for a total of four groups. The goal of 80 participants was based upon a GPower analysis for an analysis of variance, where a minimum of 80 participants were required for a larger effect size (0.4) and power value of 0.8. During recruitment, there were a limited number of participants with knowledge and experience feeling ABS activate, thus achieving the goal of 20 participants in each group was not possible.

A total of 77 participants completed this study. Eight participants were dropped because one participant did not pass the simulator practice and seven participants performed the braking exercise on an alternative track location and surface due to a scheduling conflict that impacted the instructor's ability to rate the drivers' performance. The remaining 69 participants, see Table 36, consisted of 59 males, 9 females and one participant who did not report gender, ranging in age from 18 to 60 years (M=30.9, SD=12.6). As a result of the lack of participants with prior knowledge and experience feeling ABS and dropping multiple participants, the number of participants in each group was unbalanced. There were 23 participants without knowledge and experience feeling ABS who completed the simulator group, consisting of 18 males and five females, and an average age of 33.1 years (*SD*=15.8). For the 18 participants without prior knowledge and experience who did not complete the simulator practice, there were 16 males and two females, with an average age of 24.2 (*SD*=7.9). There were a total of 15 participants who had previous knowledge and experience feeling ABS and completed the simulator practice, with 13 males and two females, and an average age of 35 (*SD*=10.8). Lastly, the 13 participants with knowledge and experience feeling ABS who did not complete the simulator practice, had 12 males and one participant that did not report gender with an average age of 30.5 (*SD*=10.7). Though these groups were unbalanced, the small number of females were distributed throughout the groups and the ages were similar between groups.

Table 36. Participant groups

ABS grouping	**Simulator practice grouping**	
	Simulator practice	**No practice (control)**
No knowledge and experience feeling ABS	23 participants Avg. age 33.1 (*SD*=15.8) 18 males, 5 females	18 participants Avg. age 24.2 (*SD*=7.9) 16 males, 2 females
Has knowledge and experience feeling ABS	15 participants Avg. age 35 (*SD*=10.8) 13 males, 2 females	13 participants Avg. age 30.5 (*SD*=10.7) 12 males, 1 did not report

10.2.1 Research Design

Participants were grouped by their previous experience with ABS as well as if they were in the simulator practice group or control group. Mims et al. (2021) identified background factors that influenced participants' ability to activate ABS on a track during the first run, which included participants that understood the feel of ABS when activated, participated in additional driver's training beyond driver's education either with or without ABS experience, or those who practiced activating ABS. The first influential factor was having prior knowledge of what ABS feels like when activated (Mims et al., 2021). For the current study, participants were first grouped by whether they did or did not have prior knowledge of what ABS feels like when activated. In total there were two levels that defined a participant's experience with ABS: did not know what ABS felt like when it is activated and did know what ABS felt like when ABS is activated. Participants were further grouped by whether they were part of the simulator practice group or part of the control group that did not experience the practice on the simulator. As a result, this study featured a 2 x 2 factorial design.

10.2.2 Materials

10.2.2.1 Driving Simulator for Emergency Braking Practice with ABS Brake Pedal Feedback

For the simulator training portion of the study, participants practiced emergency braking on a simulator with haptic ABS brake pedal feedback (see Figure 78). The simulator featured Fanatec ClubSport V3 Inverted Pedals and a ButtKicker Gamer2 mounted to the pedals set to supply haptic feedback. Aluminum extrusions created structural support for the pedal set as well as the seat to prevent tipping while practicing emergency braking. The simulator utilized DriveSafety software and related hardware. The haptic ABS feedback created by the ButtKicker Gamer2 replicates the feedback from ABS in a vehicle. The signal used for the input for the ButtKicker was captured from a professional driving instructor activating ABS in a vehicle. The feel of ABS in the simulator was verified by a subject matter expert who was a professional driving instructor. For a detailed description of the development of the simulator, please see Chapter 9 section 9.2.1.2 Simulator.

Figure 78. Simulator setup with device that delivers haptic ABS feedback circled in red (ButtKicker). The yellow circle highlights the attachment point to the pedal assembly.

10.2.2.2 Interactive Exercises

The simulator utilized DriveSafety's SimClinic software, where two different interactive exercises which focus on the gas and brake pedal were selected. Neither of the interactive exercises used a driving scene, therefore simulator sickness was never a topic of concern.

10.2.2.2.1 Pedals Chase©

The *Pedals Chase©* interactive exercise was used to practice modulating the gas and brake pedal. The interactive exercise consisted of dynamic targets on visual representations of the gas and brake pedals (see Figure 79). The participant pressed the gas or brake pedal to move the line that indicates the pedal position into the dynamic target zone that moved up and down the pedal. The moving target zone began on the gas pedal before moving to the brake pedal. Level 2 of this interactive exercise was used, where the target zone is 25% of the size of the pedal.

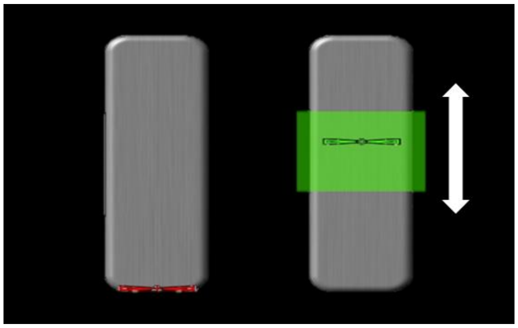


Figure 79. Pedals Chase© Level 2

10.2.2.2.2 Pedals Emergency Stop©

The *Pedals Emergency Stop©* interactive exercise was created to practice emergency braking and experience the haptic feedback from ABS that often occurs in emergency braking scenarios. The interactive exercise began with a dynamic target zone on the gas pedal (see Figure 80, left), like *Pedals Chase©* Level 2. The time the gas pedal target is in motion until the brake pedal target zone appears varies to prevent the driver from anticipating the target, but is randomized between a minimum of two to a maximum of six times the gas pedal target crosses the middle of the gas pedal. Then the brake target appeared at the top of the pedal (see Figure 80, right) and an audible “Stop” was heard to prompt the participant to quickly press the brake pedal to maximum travel. Once the brake indicator was in the target zone, the participant held the indicator in the target zone for three tones while experiencing the haptic brake pedal feedback (see Chapter 9 section 9.2.1.2.3 ABS Haptic Brake Pedal Feedback for a detailed description of the pedal feedback). The action of holding the indicator in the target zone simulated the time it takes for the vehicle to come to a stop once the brake is fully depressed.

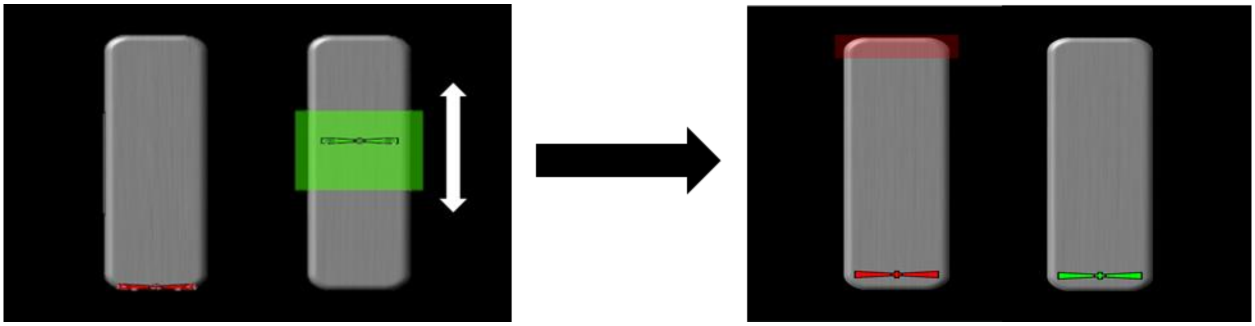


Figure 80. Pedals Emergency Stop© moving gas target (left) and brake target (right)

After responding to the brake target zone, the results were displayed to indicate the participant's performance practicing the emergency stop (see Figure 81). The practice consisted of a practice with four trials, followed by three separate tests with four trials each. The results for the practice and tests consisted of two columns, the left column labeled "Pass?", communicated performance of the emergency braking attempt. When a "Yes" was displayed, the participant pressed the brake pedal fast enough, far enough, and held the indicator in the target zone for three tones. When a "No" was displayed the participant either did not press the brake pedal fast enough and/or did not hold the indicator in the target zone for three tones. The right column labeled "Advice" offered feedback to the participant to improve their braking performance if they did not pass. If the participant did not "pass" as a result of not pressing the brake pedal fast and hard enough, the advice to "Press harder / faster" was displayed. If the participant did not hold the indicator in the brake target zone for three tones, "Hold longer" was displayed. If the participant did not press the brake pedal fast and hard enough nor held the indicator in the target zone for three tones, the participant received the advice to "Press harder / faster".

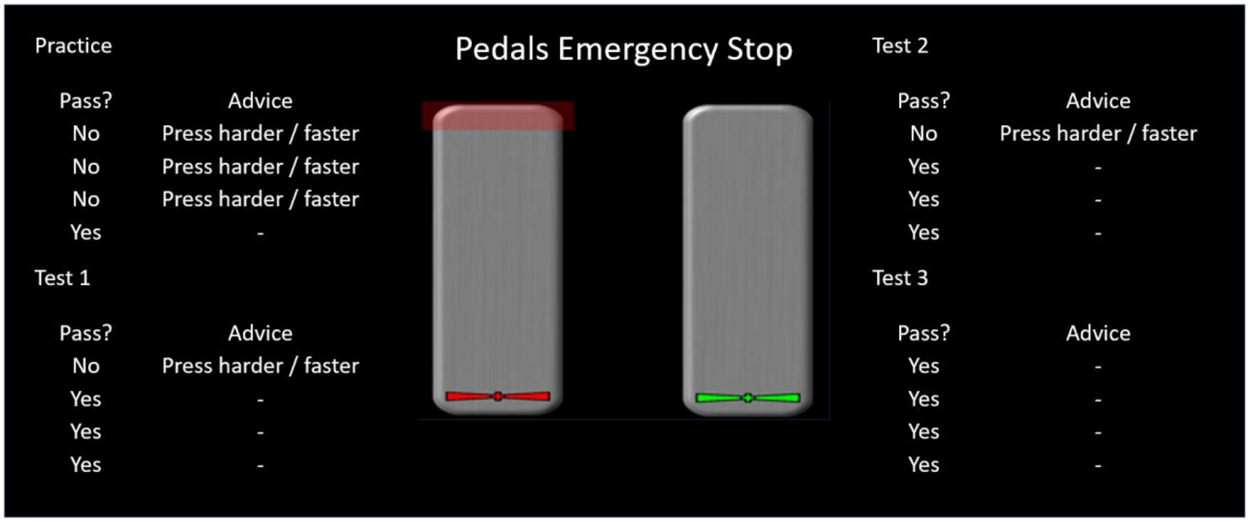


Figure 81. Example results after the first target of the Pedals Emergency Stop© interactive exercise

The four practice trials served as practice for participants to understand the interactive exercise. The criteria to pass the *Pedals Emergency Stop©* interactive exercise was to “pass” on three of the four trials within one of the tests.

10.2.2.4 Surveys and Rating Scale

10.2.2.4.1 Recruitment Questions

During recruitment, interested individuals were asked questions to determine their experience with ABS in order to group them prior to the study (see **Error! Reference source not found.**). After meeting the basic enrollment criteria for the study (e.g., age, driver’s license, physical challenges / use of adaptive equipment, left foot brakers), individuals were asked if they had ever activated ABS in a vehicle. For those who reported experiencing ABS in a vehicle, a follow-up question was asked what is felt when ABS is activated. Thudding or vibration in the brake pedal and the vehicle shakes were examples of acceptable correct responses for what is felt when ABS was activated. Of those who correctly identified what was felt when ABS was activated, they were asked if they had previously participated in driving courses beyond driver's education (e.g. BMW car control classes, M-school classes, BMW's driving certification for employees, etc.). If an individual reported training beyond driver's education, they were not eligible for the study. From Mims et al. (2021), participants who reported participating in driving courses beyond driver's education with an ABS component prior to the class had perfect performance (5 average out of 5) during the first run. For this reason, individuals who have previously taken a driving course beyond driver's education were not eligible for this study.

Table 37. Recruitment questions

Question	Response type	Eligibility
Are you between the ages of 18 and 60?	Yes / No	If no, not eligible
Do you have a driver's license?	Yes / No	If no, not eligible
Do you have any challenges with your hips, legs or feet that would prevent you from operating a vehicle?	Yes / No	If yes, not eligible
Do you ever use your left foot to brake?	Yes / No	If yes, not eligible
Do you use adaptive equipment when driving?	Yes / No	If yes, not eligible
Have you ever activated ABS in a vehicle?	Yes / No	-
- If yes, what do you feel when ABS is activated?	Open-ended (correct / incorrect)	-
○ If correct, have you participated in driving courses beyond driver's education like the BMW car control classes, M-school classes, BMW's B1 certification for employees, etc.?	Yes / No	If yes, not eligible

10.2.2.4.3 Final Survey

At the end of the study, all participants completed a short survey on their experience and to gain additional background information (see Table 38). All participants were asked to rate their competency to perform a perfect ABS stop using a 1-6 scale both prior to the study and after the practice on the track, where a rating of 1 was not competent to perform without extensive further training and a rating of 6 corresponded to fully competent to perform without further training. In addition, the group of participants who experienced the emergency braking practice on the simulator were asked to rate their competency to perform a perfect ABS stop after the simulator practice. Participants who experienced the emergency braking practice on the simulator were also asked if they thought they benefitted from the simulator practice and why they thought they did or did not.

Table 38. Final survey

Question		Response type
All participants	What is your age?	Open-ended
	What is your gender?	Open-ended
	Did you learn anything as a result of participating in this study?	Yes / No
	- If yes, what did you learn?	Open-ended
	What was the hardest part of the ABS exercise on the track?	Open-ended
	Using the scale below, please fill in the blanks using one of the 6 options below that best reflects your competency to perform a 10/10 ABS stop prior to the study, and after the practice on the track. 1. Not competent to perform without extensive further training. 2. Not competent to perform without moderate further training. 3. Not competent to perform without brief further training. 4. Minimally competent to perform without further training. 5. Moderately competent to perform without further training. 6. Fully competent to perform without further training.	1-6 scale
	Do you have any additional comments?	Open-ended
Simulator practice	Do you think you benefitted and/or performed better on the track as the result of emergency braking practice on the simulator?	Yes / No
	- Why?	Open-ended
	Using the scale below, please fill in the blanks using one of the 6 options below that best reflects your competency to perform a 10/10	1-6 scale

	ABS stop prior to the study, after the simulator practice and after the practice on the track. 1. Not competent to perform without extensive further training. 2. Not competent to perform without moderate further training. 3. Not competent to perform without brief further training. 4. Minimally competent to perform without further training. 5. Moderately competent to perform without further training. 6. Fully competent to perform without further training.	

10.2.3 Procedure

Participants were recruited through BMW corporate communications from BMW Plant Spartanburg. During recruitment, potential participants were asked the screening questions to determine if they qualified for the study. These screening questions also allowed the research team to understand potential participants previous knowledge and experience with ABS in order to be grouped for scheduling purposes.

When participants arrived for the study were consented and designated to the proper group, either the simulator group or the control group (no simulator practice). Drivers were given colored wristbands that designated their group membership. Written on the wristbands was the vehicle number, which corresponded to the numbered vehicle the driver drove during the track portion, and the driver number, which indicated if the participant was the driver or passenger first. Participants assigned to the simulator group first completed the emergency braking practice on the simulator prior to other study activities.

10.2.3.1 Emergency Braking Practice on the Simulator

For the participants in the simulator practice group, the simulator protocol began with the participant adjusting themselves to a comfortable distance from the pedals, where they were able to press both pedals to maximum travel. Once at a comfortable distance from the pedals, participants completed a short familiarization task, where participants pressed each pedal to the maximum travel five times, alternating between the gas and brake pedal. Next, participants completed *Pedals Chase©* Level 2 to ensure that participants possess the motor control needed to modulate the gas pedal during *Pedals Emergency Stop©*. Participants could make up to three errors during *Pedals Chase©* and have up to three trials to complete the task with three errors or less (Brooks et al., 2016). Participants then received the description of emergency braking, which contained of an explanation of ABS, **"**For this task, you will be practicing emergency braking. During 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 (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." Participants completed the *Pedals Emergency Stop©* interactive exercise, consisting of a practice with four trials followed by three tests with four trials each. If participants "passed" three out of four trials in a test, they passed the simulator practice. All participants completed the practice and all three tests (16 total trials) regardless of whether a participant "passed" the test or not to ensure that all participants received the same amount of practice.

10.2.3.2 Classroom Instructional Video

Next, all participants watched a video of a professional driving instructor giving an overview of proper seating adjustments, hand positioning, and where to look while driving. The instructor then gave an overview of ABS, including the purpose of the system, how it functions and how to properly brake in an emergency. The participants were instructed to keep one's eyes up, looking where they want to go (rather than looking down inside the vehicle), stomp on the brake pedal and keep the brakes fully depressed until the vehicle comes to a complete stop. The duration of the video was 10 minutes.

10.2.3.3 ABS Exercise on the Track

After the completion of the video in the classroom, participants moved outside to complete the ABS exercise on the track. On the day of the research study, it was sunny and dry with the temperature near 90ºF. Participants got into the assigned vehicles based on the vehicle number on their wristband. There were up to two participants per vehicle, where one participant started as the driver and the other was a passenger. Participants drove 2022 BMW M230i sedans during the ABS exercise. The ABS exercise was located on a longer slightly curved portion of the track (see Figure 82 left). As an introduction to the ABS braking exercise, participants stood near the braking area of the track while the professional driving instructor performed a demonstration of the ABS stop. The instructor sped up from the starting point to a speed of 35mph and performed an ABS stop, began to brake at a set of cones. Researchers were positioned in a parking lot near, but off the track (see Figure 82 right). After the demonstration participants drove to the starting point forming a line and the instructor moved near the braking location on the track in order to give feedback to the participants on their performance (see Figure 82 right).

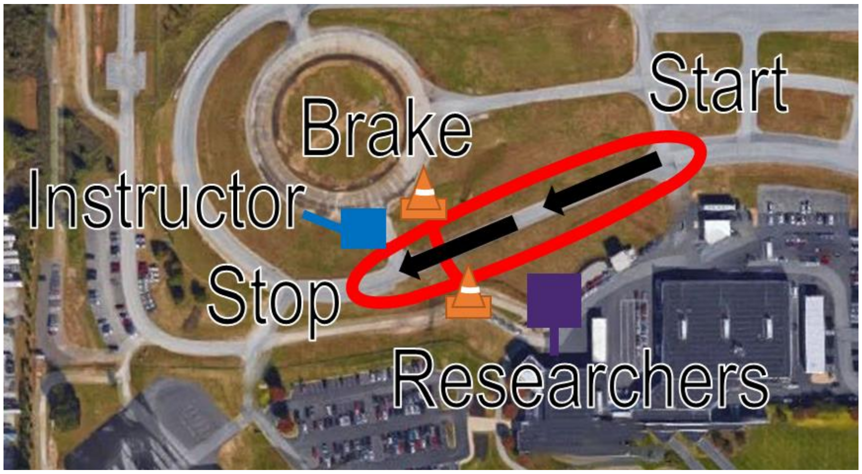


Figure 82. Map of the ABS exercise

To begin the ABS exercise, the driver sped up to 35 mph and maintained that speed until the driver reached the set of cones, where the driver began to brake and attempted to activate ABS. After each run, the driver received feedback on their performance activating ABS over a two-way radio that all participants heard and then drove back to the start of the course. Then, the instructor communicated with the researchers via a second two-way radio, that only the researcher and instructor could hear, regarding the rating that described the participant's performance activating ABS (see Table 35; Mims et al., 2021). The researcher located off the track recorded the feedback and rating associated with each participant's runs. Participants completed a total of five runs at 35 mph. After the first group of drivers completed their runs, the drivers and passengers switched roles and completed their five runs of the ABS exercise.

As an incentive for participating in this study, participants were given the opportunity to complete the performance center's off-road course. Participants drove 2022 BMW X3 SUV's through the off-road course with a different instructor. At the end of the study participants returned to the classroom where they completed the final survey and had the option to enter the drawing for a free two-day performance driving class offered as an incentive to the research participants.

10.2.5 Measured Variables

10.2.5.1 Independent variables

The independent variables included practice group membership (simulator practice, no simulator practice) and previous experience with ABS (never experienced ABS, experienced ABS before). Within the simulator group, the test that the participant “passed” three out of four trials was included as an independent variable.

10.2.5.2 Dependent variables

The dependent variables from the simulator were the test when participants “passed” three out of the four trials, the number of trials for a participant to “pass” for the first time, and the number of participants to pass and fail on each trial.

The dependent variables from the track included the number of trials taken to fully activate ABS with a rating of 5 for the first time, participants’ rating for the first trial, and participants’ ratings over all 5 trials.

10.2.6 Research Questions and Hypotheses

10.2.6.1 Research Question and Hypothesis 1

The first research question investigated was: Can the *Pedals Emergency Stop*© interactive exercise help reduce the number of trials needed to fully activate ABS on a track for drivers without previous ABS experience? The corresponding hypothesis was: Drivers without previous ABS experience who complete the *Pedals Emergency Stop*© interactive exercise will fully activate ABS on a track in a fewer number of trials than drivers who do not complete the *Pedals Emergency Stop*© interactive exercise. This was expected because Mims et al. (2021) found that adult drivers who had been trained or have previous experience practicing activating ABS had significantly higher performance completing an ABS stop on a track compared to drivers without those experiences. If a driver experiences the *Pedals Emergency Stop*© interactive exercise to gain practice with emergency braking with ABS, they are expected to perform better.

10.2.6.2 Research Question and Hypothesis 2

The second research question investigated was: Can the *Pedals Emergency Stop*© interactive exercise help increase the likelihood of a driver without previous ABS experience fully activate ABS on a track during their first trial? The corresponding hypothesis was: More drivers without previous ABS experience who complete the *Pedals Emergency Stop*© interactive exercise will fully activate ABS on a track during the first trial compared to drivers who do not complete the *Pedals Emergency Stop*© interactive exercise. This result was expected due to the findings from Mims et al. (2021), where drivers with previous practice or training with ABS had significantly higher ratings on the first run compared to drivers without those experiences.

10.2.6.3 Research Question and Hypothesis 3

The third research question investigated was: Can the *Pedals Emergency Stop*© interactive exercise help increase the number of trials where ABS was fully activated on a track for drivers without previous ABS experience? The corresponding hypothesis was: More drivers without previous ABS experience who completed the *Pedals Emergency Stop*© interactive exercise fully activated ABS on the track on more trials compared to drivers who do not complete the *Pedals Emergency Stop*© interactive exercise. This result was expected due to the findings identified by Mims et al. (2021), which found that drivers with previous practice or training with ABS had significantly higher ratings on the first run compared to drivers without those experiences.

10.2.7 Data Analysis

An analysis of variance was conducted to determine if the participants who completed the *Pedals Emergency Stop*© interactive exercise without previous knowledge and experience feeling ABS activate, fully activated ABS on the track in fewer attempts than those who did not complete the *Pedals Emergency Stop*© interactive exercise. The dependent variable was the number of attempts to fully activate ABS on the track and the independent variable was the ABS experience and simulator practice grouping (four groups).

A second analysis of variance was conducted to determine if more participants who completed the *Pedals Emergency Stop*© interactive exercise without previous knowledge and experience feeling ABS activate, fully activated ABS on the track during the first attempt than those who did not complete the *Pedals Emergency Stop*© interactive exercise. The dependent variable was the participants' ratings during first attempt and the independent variable was the ABS experience and simulator practice grouping (four groups).

A third analysis of variance was completed to determine if participants who completed the *Pedals Emergency Stop*© interactive exercise fully activated ABS on the track on more trials than the participants who do not complete the *Pedals Emergency Stop*© interactive exercise, particularly for participants without previous experience feeling ABS activate. The dependent variable was the participants’ ratings for all trials and the independent variable was the ABS experience and simulator practice grouping (four groups).

Additional analyses were conducted to determine if there were differences in performance within the simulator practice group. To determine if there were significant differences on the test number the participants “passed” the simulator practice between participants with and without prior knowledge and experience feeling ABS activate, Chi-square tests were conducted. To determine if there were significant differences in the number of trials to “pass” for the first time between participants with and without prior knowledge and experience feeling ABS activate, an analysis of variance was conducted.

10.3 Results

10.3.1 Simulator Practice

For the 39 participants that completed the simulator practice, all participants were able to pass the warmup exercise, *Pedals Chase©*, with three errors or less within three attempts. All but one participant was able to pass the emergency braking practice on the simulator by “passing” three out of four trials within a test. The participant did not pass the simulator practice did not “pass” any trials and was excluded from the analyses.

For the 38 participants who were able to “pass” three out of four trials of a test and thus passed the emergency braking practice on the simulator, 94.7% of participants passed during Test 1, 2.6% passed during Test 2, and 2.6% passed during Test 3. The participant that passed during Test 2 did not have prior knowledge and experience feeling ABS activate, where the participant that passed during Test 3 did have prior knowledge and experience feeling ABS activate. All 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 participants "passed" for the first time in 1.8 trials (*SD*=1.3), where 94.7% of participants were able to "pass" during the practice (within the first four trials). For participants without prior experience with ABS, the average number of trials to "pass" for the first time was 1.7 trials (*SD*=1.1), which was similar to the 1.9 average trials (*SD*=1.6) it took for the participants with prior knowledge and experience feeling ABS activate to "pass" for the first time. There were no significant differences between the average number of trials for participants to "pass" for the first time between participants with and without knowledge and experience with ABS.

For the 61 trials that participants did not "pass", 95% of the feedback was to "Press harder and faster" and only 5% of the feedback was to "Hold longer".

10.3.2 On-track Braking Exercise

All participants completed five runs or attempts during the braking exercise on the track.

10.3.2.1 Number of Attempts to Fully Activate ABS

On average, participants needed an average of 1.9 attempts (*SD*=0.9) to receive a rating of 5, fully activating ABS throughout the entire stop. Ninety-six percent of the participants were able to receive a rating of 5 during their five attempts on the track. Three participants never received a rating of 5, where a rating of 4 was the highest rating all three participants received. For participants that completed the simulator practice, it took an average of 2 trials (*SD*=1.2) to fully activate ABS for those without knowledge and experience feeling ABS activate and for those with prior knowledge and experience with ABS, it took an average of 1.9 trials (*SD*=0.7) to fully activate ABS. Participants in the control group that did not receive the simulator practice with no knowledge and experience feeling ABS fully activated ABS in an average of 1.7 trials (*SD*=0.8) and 1.9 trials (*SD*=0.9) for those with prior experience feeling ABS (see Table 39). Interestingly, the three participants that were not able to fully activate ABS were all participants without previous knowledge and experience feeling ABS, where one had the simulator practice and two did not.

Table 39. Average number of attempts to fully activate ABS (rating of 5) by group

Attempts to fully activate ABS	Simulator practice	Control
No knowledge and experience feeling ABS	2.0 (SD=1.2)*	1.7 (SD=0.8)**
Has knowledge and experience feeling ABS	1.9 (SD=0.7)	1.9 (SD=0.9)

*One participant in this group never fully activated ABS and received a rating of 5.
**Two participants in this group never fully activated ABS and received a rating of 5.

The results of the analysis of variance did not find any significant differences or interactions in the number of trials for participants to fully activate ABS between participants with and without prior experience feeling ABS activate as well as those who had and did not have the emergency braking practice on the simulator. Despite the groups being unbalanced, there were no significant differences in variance found between the groups.

10.3.2.2 Performance During the First Attempt

For the first attempt of the braking exercise, the average rating across all participants was 3.6 (*SD*=1.4), where 39% of the participants received a rating of 5 (full ABS activation throughout the entire stop). The average rating for the first attempt of the braking exercise for participants that completed the simulator practice was 3.6 (*SD*=1.5) for those without knowledge and experience feeling ABS activate and similarly, 3.6 (*SD*=1.2) for those with prior knowledge and experience with ABS. Participants in the control group that did not receive the simulator practice with no knowledge and experience feeling ABS had an average rating of 3.7 (*SD*=1.4) on the first attempt and 3.5 (*SD*=1.6) for those with prior experience feeling ABS (see Table 40).

Table 40. Average rating for the first attempt of the braking exercise by group

Average rating for first attempt	Simulator practice	Control
No knowledge and experience feeling ABS	3.6 (SD=1.5)	3.7 (SD=1.4)
Has knowledge and experience feeling ABS	3.6 (SD=1.2)	3.5 (SD=1.6)

The results of the analysis of variance revealed no significant differences or interactions in the rating for the first attempt of the braking exercise between participants who had and had not completed the simulator practice nor participants with and without prior experience feeling ABS activate. Interestingly, there were no significant differences in variance found between the groups, even though they were unbalanced.

An exploratory analysis was conducted to determine if there were differences in the number of participants that received a rating of 5 or fully activated ABS during the first attempt between the four groups. The ratings were treated as a pass or fail, where a rating of 5 indicated a pass and ratings 1-4 indicated a fail. A Chi-square test was conducted, but there were no significant differences found in the number of participants to fully activate ABS during the first attempt between groups.

10.3.2.3 Performance Across All Attempts

To understand performance during all runs or attempts of the braking exercise, the ratings from all five attempts were averaged. For all participants, the average rating across all attempts was 4.3 (*SD*=1.2). Interestingly, the average rating across all attempts did not vary much between the groups, where the average rating for participants in the simulator and control group without knowledge and experience feeling ABS was 4.3 (SD=1.3) and 4.4 (SD=1.1) for participants in the simulator and control group with prior knowledge and experience with ABS (see Table 41).

Table 41. Average rating across all five attempts of the braking exercise by group

Average rating for all five attempts	**Simulator practice**	**No practice (control)**
No knowledge and experience feeling ABS	4.3 (SD=1.3)	4.3 (SD=1.3)
Has knowledge and experience feeling ABS	4.4 (SD=1.1)	4.4 (SD=1.1)

Since the average ratings across all groups were similar, as expected, the results of the analysis of variance showed no significant differences or interaction in average rating between the groups. There were no significant differences in variance found between the groups, even though the groups were unbalanced.

An exploratory analysis was conducted to determine if there were differences in the number of participants that received a rating of 5 or fully activated ABS across all attempts between the four groups. The ratings were treated as a pass or fail, where a rating of 5 indicated a pass and ratings 1-4 indicated a fail. A Chi-square test was conducted, but there were no significant differences found in the number of participants to fully activate ABS for attempts between groups.

10.3.2.4 Instructor Feedback

During the braking exercise, participants received feedback on their performance after each run if they did not fully activate ABS. From Mims et al. (2021), the common feedback given to participants was: *Press the pedal and keep it pressed until the vehicle comes to a complete stop*; *Press the brake harder* or *Press the brake as hard as you can*; and *Slam the pedal from the start* (of the stop) *instead of easing onto it.* The most common feedback the participants received was to *Press the brake harder* or *Press the brake as hard as you can (53)* and *Slam the pedal from the start instead of easing onto it (26)*. There were only three times participants were given the feedback to *Press the pedal and keep it pressed until the vehicle comes to a complete stop.* As the number of runs increased, the amount of feedback decreased (see Table 42).

Table 42. Instructor feedback for each run of the braking exercise

	Feedback			
Run	Press the brake harder or as hard as you can	Slam the pedal from the start instead of easing onto it	Press the pedal and keep it pressed until the vehicle comes to a complete stop	Feedback count for each run
Run 1	18	18	1	37
Run 2	14	1	2	17
Run 3	9	4	0	13
Run 4	7	2	0	9
Run 5	5	1	0	6
Count for each feedback type	53	26	3	

10.3.3 Survey Results

10.3.3.1 Learning from the Study

All participants were asked if they learned anything as a result of participating in the study, where 91% of the participants reported learning from the study and only 9% did not learn anything from participating in the study. For the participants that reported learning from the study, they were asked what they learned. The most common responses were what ABS is and how to use it (25%), how hard and far to press the brake pedal (25%), the feel / feedback from ABS (13%), and the importance of braking early (10%). Other less common responses were focused on the capabilities of the BMW vehicles driven (8%), overcoming the fear of hard braking (6%), and how powerful / violent hard braking is (5%). The remaining responses (8%) did not overlap with other participants' responses and were unique to the individual.

10.3.3.2 Hardest Part of the Braking Exercise on the Track

All participants were asked what they thought the hardest part of the braking exercise on the track was. The most common responses were maintaining the speed (35%), pressing the brake pedal hard (21%), and nothing (12%). Some of the other common responses given by participants included the fear of the harshness of hard braking (6%), being a passenger (3%), holding the brake pedal position (3%), trusting the vehicle would stop (3%), transitioning from the gas pedal to the brake pedal (3%), and adjusting or getting used to the vehicle (3%). The remaining responses (11%) were unique to the individual and did not overlap with other participants' responses.

10.3.3.3 Benefitted and/or Performed Better on the Track as a Result of the Emergency Braking Practice on the Simulator

Participants that completed the emergency braking practice on the simulator were asked if they thought they benefitted and/or performed better on the track as a result of the braking practice on the simulator. Of the 38 participants that successfully completed the simulator practice, 74% thought they benefitted from the simulator practice and 26% did not think they benefitted. All participants were asked why they thought they either benefitted or did not benefit from the simulator practice. For the participants that thought they benefitted and/or performed better on the track as a result of the simulator practice, common responses for why they thought they benefitted included the simulator practice demonstrated how hard to press the brake (44%), helped to know what to expect on the track (19%), learned what ABS feels like (11%), and practiced transitioning from the gas to the brake pedal (7%). The remaining responses (19%) did not overlap with other participants' responses, which included "learning the ABS was helpful", "I've used ABS before", "I got the chance to drive and experience it", "be more consistent", and "repetition builds memory". For the participants that did not think they benefitted and/or performed better on the track as a result of the simulator practice, responses to why participants did not feel as though they benefitted included the simulator was not realistic of a real situation (40%), the simulator setup was not representative of a real vehicle (30%), the simulator practice was easy / simple (20%), and one participant (10%) thought the simulator practice was more difficult than braking in the vehicle.

10.3.3.4 Competency to Perform an ABS Stop

All participants were asked to rate their competency to fully activate ABS on the track prior to the study and after the practice on the track using a 1 to 6 scale, where a rating of 1 corresponded to not competent to perform without extensive further training and a rating of 6 corresponded to fully competent to perform without further training. Participants that completed the simulator practice were asked to rate their competency after the emergency braking practice on the simulator. Interestingly, eight participants responded with ratings greater than 6 and as a result, were not included in the calculations. For competency ratings prior to the study, participants without prior knowledge and experience feeling ABS in both the simulator practice (M=4.2, SD=1.0) and control group (M=3.7, SD=1.5) had lower starting competency ratings compared to the participants who had previously experienced ABS in both the simulator practice (M=4.8, SD=0.6) and control group (M=4.4, SD=0.5). There was an increase in competency rating for participants that completed the simulator practice between their ratings prior to the study and after the simulator practice, both for participants with (0.4 increase) and without (0.5) knowledge and experience feeling ABS activate. There were larger increases in competency between the ratings prior to the study to after the practice on the track for all groups, where participants that completed the simulator practice without prior ABS experience had an average competency rating of 5.7 (*SD*=0.6) and 5.9 (*SD*=0.3) for participants with prior experience feeling ABS activate. Similarly, participants that did not complete the simulator practice without prior ABS experience had an average competency rating of 5.6 (*SD*=0.5) and 5.6 (*SD*=0.5) for participants with prior experience feeling ABS activate (see Table 43). After the practice on the track, on average, all participants regardless of group felt moderately to fully competent to fully activate ABS.

Table 43. Competency to fully activate ABS prior to the study, after the simulator practice and after the practice on the track by group

Competency rating	Prior to the study	After the simulator practice	After the practice on the track
No knowledge and experience feeling ABS – Simulator practice (N=21)	4.2 (*SD*=1.0)	4.9 (*SD*=0.8)	5.7 (*SD*=0.6)
No knowledge and experience feeling ABS – Control (N=15)	3.7 (*SD*=1.5)	-	5.6 (*SD*=0.5)
Has knowledge and experience feeling ABS – Simulator practice (N=13)	4.8 (*SD*=0.6)	5.2 (*SD*=0.6)	5.9 (*SD*=0.3)
Has knowledge and experience feeling ABS – Control (N=12)	4.4 (*SD*=0.5)	-	5.6 (*SD*=0.5)

An exploratory analysis of covariance (ANCOVA) was conducted to determine if there were differences in self-reported competency after the practice on the track based upon prior knowledge and experience with ABS as well as completion of the simulator practice. The competency rating prior to the study was treated as a covariate, which was found to be positively correlated to the competency rating after the practice on the track (r=0.53, $p<0.05$). The results did not reveal any difference in competency ratings after the practice on the track between participants who had and did not have prior experience feeling ABS, nor completed or did not complete the simulator practice.

10.4 Discussion

The goal of this study was to evaluate if an emergency braking practice that utilized the *Pedals Emergency Stop*© interactive exercise impacted a driver's ability to fully activate ABS on a track. The *Pedals Emergency Stop*© interactive exercise prompted individuals to practice 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, then a stationary brake pedal target appears at the very top of the brake pedal at the same time a "Stop" prompt is played. 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, 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. Participants had to “pass” three out of four trials on a test to pass the simulator practice. After the simulator practice, participants completed a braking exercise on the track, where participants sped up to 35mph and attempted to brake hard enough to activate ABS five times. A professional driving instructor rated the participants’ ability to activate ABS during each attempt using a behaviorally anchored rating scale with five ratings (Mims et al., 2021), where a rating of 1 indicated no ABS activation and rating of 5 corresponded to fully ABS activation throughout the entire stop. A total of 69 participants completed this study, ranging from 18 to 60 years of age. Participants were in one of four groups based upon their knowledge of and experience feeling ABS prior to the study as well as if they completed the simulator practice or not (control group).

The results from the participants that completed the simulator practice showed that all but one of the 39 participants was able to pass the emergency braking practice. Since 94.7% of the participants were able to pass the emergency braking practice during Test 1, these results suggest that the criteria of “passing” three out of four trials within a test was achievable for almost all participants. Also, 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, participants in this study “passed” for the first time in an average of 1.8 trials which is a fewer number of trials observed in the previous study (Chapter 9), where participants “passed” for the first time in an average of 3 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 (Chapter 9), 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 (Chapter 9), the majority of the advice given to participants that did not “pass” a trial was to “Press harder and faster”. The results of the this suggest the updates to the *Pedals Emergency Stop©* interactive exercise helped improve participants’ performance during the exercise and the criteria to pass the emergency braking practice is representative of a participant that is successful passing.

The results from the track portion of the study did not reveal any significant differences between the participants that had completed the simulator practice and those who did not (control group), nor between participants who had and did not have prior knowledge and experience feeling ABS activate. Interestingly, Mims et al. (2021) did find significant differences in participants that had and did not have previous experience feeling ABS activate. Participants that did not know what ABS felt like when activated from Mims et al. (2021) study had an average rating of 3.3 on the first run of the braking exercise and participants that did know what ABS felt like had an average rating of 4.1 on the first run. For participants in the current study, participants that did not have experience feeling ABS activate, had higher ratings on the first run (3.6 for simulator practice and 3.7 for control group) compared to the participants from Mims et al. (2021). Participants in the current study with previous experience feeling ABS activate had lower average ratings during the first run (3.6 for simulator practice and 3.5 for control group) compared to participants with knowledge of what ABS feels like from Mims et al. (2021). These differences could be due to the difference in participant population, where participants in the current study were volunteers and participants from Mims et al. (2021) were paying customers enrolled in a defensive driving class.

The most common feedback given to the participants during the braking exercise on the track was to brake harder, followed by slam on the brake from the beginning instead of easing onto it. The most common feedback given to participants in the study by Mims et al. (2021) was to press the brake pedal and keep it pressed until the vehicle comes to a complete stop, followed by brake harder and slam on the brake from the beginning instead of easing onto it. These differences may be due to the differences in speeds driven by drivers in the studies. In the current study, all participants completed five runs at 35mph and participants in the Mims et al. (2021) study completed seven runs ranging in speed from 30 to 60mph, increasing incrementally with the run number. As speed increases, stopping distance increases exponentially as well as the time the driver is maintaining brake pedal position and pressure. Since participants in the current study completed the braking exercise at 35mph, the time to maintain brake pedal position and pressure did not change. Participants in the Mims et al. (2021) study had to maintain brake pedal position and pressure for longer periods as the speed and stopping distance increased over their seven runs. This is likely why participants in the Mims et al. (2021) study received the feedback to press the brake pedal and keep it pressed until the vehicle came to a complete stop much more frequently compared to the current study.

10.4.1 Discussion of Research Question and Hypothesis 1

The first research question was: Can the *Pedals Emergency Stop*© interactive exercise help reduce the number of trials needed to fully activate ABS on a track for drivers without previous ABS experience? The corresponding hypothesis was: Drivers without previous ABS experience who complete the *Pedals Emergency Stop*© interactive exercise will fully activate ABS on a track in a fewer number of trials than drivers who do not complete the *Pedals*

Emergency Stop© interactive exercise. This was expected because Mims et al. (2021) found that adult drivers who had been trained or have previous experience practicing activating ABS had significantly higher performance completing an ABS stop on a track compared to drivers without those experiences. If a driver experiences the *Pedals Emergency Stop*© interactive exercise to gain practice with emergency braking with ABS, they are expected to perform better.

The results of the ANOVA revelated there was no main effect of ABS experience, thus drivers with previous knowledge and experience feeling ABS did not fully activate ABS on the track any sooner than those without knowledge and experience with ABS. The results of the ANOVA also revealed there was no main effect of the simulator practice with the *Pedals Emergency Stop*© interactive exercise, thus drivers that completed the simulator practice did not fully activate ABS on the track sooner than those who did not complete the simulator practice. The results suggest the ability of a participant to fully activate ABS on the track is not dependent on their previous knowledge and experience feeling ABS activate, nor completing the simulator practice with the *Pedals Emergency Stop*© interactive exercise.

10.4.2 Discussion of Research Question and Hypothesis 2

The second research question investigated was: Can the *Pedals Emergency Stop*© interactive exercise help increase the likelihood of a driver without previous ABS experience fully activate ABS on a track during their first trial? The corresponding hypothesis was: More drivers without previous ABS experience who complete the *Pedals Emergency Stop*© interactive exercise will fully activate ABS on a track during the first trial compared to drivers who do not complete the *Pedals Emergency Stop*© interactive exercise. This result was expected due to the findings from Mims et al. (2021), where drivers with previous practice or training with ABS had significantly higher ratings on the first run compared to drivers without those experiences.

The results of the ANOVA revelated there was no main effect of ABS experience, thus drivers with previous knowledge and experience feeling ABS did not fully activate ABS more often on the first trial on the track than those without knowledge and experience with ABS. The results of the ANOVA also revealed there was no main effect of the simulator practice with the *Pedals Emergency Stop*© interactive exercise, thus drivers that completed the simulator practice did not fully activate ABS on the track more often during the first trial than those who did not complete the simulator practice. The results suggest the ability of a participant to fully activate ABS on the track during the first trial is not dependent on their previous knowledge and experience feeling ABS activate, nor completing the simulator practice with the *Pedals Emergency Stop*© interactive exercise.

10.4.3 Discussion of Research Question and Hypothesis 3

The third research question investigated was: Can the *Pedals Emergency Stop*© interactive exercise help increase the number of trials where ABS was fully activated on a track for drivers without previous ABS experience? The corresponding hypothesis was: More drivers without previous ABS experience who completed the *Pedals Emergency Stop*© interactive exercise fully activated ABS on the track on more trials compared to drivers who do not complete the *Pedals Emergency Stop*© interactive exercise. This result was expected due to the findings identified by Mims et al. (2021), which found that drivers with previous practice or training with ABS had significantly higher ratings on the first run compared to drivers without those experiences.

The results of the ANOVA revelated there was no main effect of ABS experience, thus drivers with previous knowledge and experience feeling ABS did not fully activate ABS more often on the track than those without knowledge and experience with ABS. The results of the ANOVA also revealed there was no main effect of the simulator practice with the *Pedals Emergency Stop©* interactive exercise, thus drivers that completed the simulator practice did not fully activate ABS on the track more often than those who did not complete the simulator practice. The results suggest the ability of a participant to fully activate ABS on the track during is not dependent on their previous knowledge and experience feeling ABS activate, nor completing the simulator practice with the *Pedals Emergency Stop©* interactive exercise.

10.5 Conclusions

The goal of this study was to evaluate if an emergency braking practice that utilized the *Pedals Emergency Stop©* interactive exercise impacted a driver's ability to fully activate ABS on a track. The emergency braking practice on the simulator allowed participants to practice with brake pedal press and experience the haptic feedback associated with ABS. In order to "pass" a trial, 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. Participants had four practice trials followed by three tests with four trials in each test. To pass the emergency braking practice on the simulator, participants had to "pass" three out of four trials within a test. A group of participants completed the simulator practice, while another group of participants did not for comparison purposes. All participants attempted to activate ABS on the track, where their performance braking was rated by a professional driving instructor using a behaviorally anchored rating scale consisting of five ratings, ranging from 1 representing no ABS activation to 5 corresponding to full ABS activation throughout the entire stop (Mims et al., 2021). The results of the simulator practice revealed that the criteria to pass three out of four trials was representative of a participant that is successful passing. There were no significant differences in braking performance on the track between participants that had completed the simulator practice and those who had not. This was also true for participants with and without prior experience feeling ABS activate, where no differences were found in performance braking on the track. Though performance was not affected by the simulator practice, 74% of the participants that completed the simulator practice thought they benefitted and/or their performance on the track was improved as a result of the emergency braking practice on the simulator with *Pedals Emergency Stop©*.

10.6 Limitations

The participant population consisted of volunteers from the same manufacturing facility. Many of the volunteers knew each other and often spoke with each other between study activities.

10.7 Future Research

Future studies should include larger sample sizes to increase the statistical power of the results. The speed of 35mph was selected because it is the speed where most crashes occur. Future studies should include multiple speeds, both lower (35-45mph) and higher speeds (50-60mph) for the braking activity in order to make the ratings consistent with the earlier studies. Mims et al. (2021) observed that speeds between 35 and 50mph corresponded to drivers learning how hard and how quickly to press the brake pedal. As the speeds increased over 50mph, the stopping distance increased, thus drivers learned to maintain brake pedal position and pressure until the vehicle came to a complete stop. The inclusion of instrumentation, including a linear potentiometer and CAN Bus recorder, may also be desirable for future studies to measure pedal position to determine if there are any differences in pedal depression speeds and reaction times between participants who complete the simulator practice and those who did not. 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 different age groups to understand if age has any effect on performance. Important age groups to consider would include new, teen drivers ideally in drivers' education courses, middle aged drivers with an inclusion of more female drivers, and older adults.

10.8 Practical Applications

The results of this study suggest that the criteria used to determine if a participant passed the emergency braking practice on the simulator was representative of the participant being proficient, regardless of an individual's previous knowledge and experience with ABS.

CHAPTER 11: DISSERTATION CONCLUSIONS AND FUTURE APPLICATIONS

This chapter aims to provide a summary of the major conclusions from each study within this dissertation as well as how these findings apply to the future of the automotive industry. The purpose of this dissertation was to understand that not all drivers have knowledge of and experience with ABS and explore the development and evaluation of a driving simulator for emergency braking training with haptic brake pedal feedback.

11.1 Conclusions from the Research Studies

The first three studies (Chapters 3-5) investigated driver's views of different post-license advanced driving programs and what the driver's main take-aways were.

The first study (Chapter 3) investigated teen diver's views of a half day defensive driving program, the Guard Your Life (GYL) Challenge program. The program consisted of a hands-on introduction to emergency braking, skid recovery and the dangers of distracted driving Participating teens (N=134) completed a survey directly after the program as well as phone interviews (N=50) three months after the program. The results from the survey reflected the program's key concepts, which including ABS braking, skid recovery and the dangers of distracted driving. The results from the phone interview revealed the most important skill used on the road and to avoid crashes from the teens' perspective was emergency braking with ABS. These results suggested that teen drivers may not understand or have experience activating ABS prior to the program (Mims et al., 2020b).

An observation made during the first study, was that the parents of the teens were engaged during the program even though they were simply watching their teens. As a result, the second study (Chapter 4) gained the parents' views (N=134) of the GYL program, in addition to a new group of teen drivers (N=164). Participating teens and their parents completed a survey directly after the GYL program. Like the previous study with GYL (Mims et al., 2020b), the teens' survey responses reflected the key concepts from the program including ABS braking, skid recovery and the dangers of distracted driving. Interestingly, the information learned during the classroom portion of the program (i.e., positing in the vehicle, where to look while driving, function of vehicle safety systems, etc.) may not have been known by the parents, and many of the parents would consider additional training for themselves after observing their teen complete the GYL program. The results suggest that parents or adult drivers may not understand or have experience activating ABS either (Mims et al., 2020a).

The third study (Chapter 5) investigated both teens' and adults' views of a one-day car control class focused on defensive driving skills. Participating teens (N=80) and adults (N=177) completed a survey directly after their respective classes, and the adults participated in a phone interview (N=64) six months after the class. The survey results showed that both the teens and adults reported the most important topics from the class were skid recovery, emergency braking with ABS, and looking where the car should go. The results from the phone interview with the adult participants, showed that emergency braking with ABS was the most used skill on the road and to avoid crashes. The results suggest that neither adults nor teens had an understanding or experience activating ABS prior to the class and practice activating ABS may be an essential skill (Mims et al., 2020c).

The results from the first three survey studies (Chapters 3-5) indicated that emergency braking with ABS was the most important skill both teen and adult drivers gained from two different post-license advanced driving programs, GYL and the one-day car control classes.

The fourth study narrowed the focus to determine high school students' knowledge and experience with ABS. High school participants recruited from science classes with a driver's license completed the survey (N=60). The results concluded that the majority of teen drivers did not have knowledge of and experience with ABS. Interestingly, there were no statistical differences in knowledge or experience with ABS between teens that had taken driver's education and those who had not. This study suggests that teen drivers, regardless of driver's education experience, did not have knowledge of or experience with ABS.

Understanding that not all drivers may have knowledge of or experience with ABS, the next study (Chapter 7), investigated how a driver's knowledge of and experience with ABS effected the driver's ability to activate ABS on a track. Adults participating in the one-day car control class were recruited to complete a survey before the class started, to gain the drivers initial knowledge and experience with ABS (N=79). During the ABS exercise on the track, the professional driving instructor rated the participants performance activating ABS using a behaviorally anchored rating scale with five ratings, where 1 equated to no activation and a rating of 5 corresponded to full ABS activation throughout the entire stop. The results of this study found that drivers with prior knowledge and experience activating ABS were more likely to fully activate ABS during their first of multiple attempts and needed fewer attempts to fully activate ABS on the track. The results of this study suggest that practice or training with ABS activation may be required in order to fully activate ABS in a vehicle (Mims et al., 2021).

Study six (Chapter 8), was a smaller study within study five (Chapter 7), where participants were adult drivers enrolled in the one-day car control classes. This study aimed to investigate variations in electrodermal activity (EDA) while drivers were completing the ABS exercise on the track. Seventeen participants wore an Empatica E4 device that measured EDA on each wrist. The EDA data were analyzed through skin conductance level (SCL), but the results showed no significant differences in SCL values between the right and left wrists, nor was there any consistency for which wrist had higher SCL values. The results from this study suggested that SCL may not be the correct measure of EDA for an ABS braking task.

Understanding that not all drivers have knowledge of and experience with ABS, as well as that knowledge and experience does affect a driver's ability to activate ABS in a vehicle, the seventh study (Chapter 9) introduced and evaluated a novel emergency braking training method, utilizing a driving simulator and an interactive exercise for emergency braking with haptic ABS brake pedal feedback, the *Pedals Emergency Stop©* interactive exercise. The exercise was designed to prompt participants to press the brake pedal in a motion consistent with emergency braking and experience haptic ABS feedback simultaneously. The exercise had a pass / fail criteria for each trial, where participants passed if they depressed the brake pedal quickly to the maximum travel and held that pedal position. A usability study (N=24) first ensured that the exercise and simulator worked as designed. The usability study provided valuable feedback from participants on both the exercise and instructions. The larger evaluation of the emergency braking practice with the *Pedals Emergency Stop©* interactive exercise included a total of 61 participants. The results showed that participants took an average of three trials to pass and 85% of participants were able to pass within the first four trials. Surprisingly, there were no differences in performance between participants who had and did not have previous knowledge and experience feeling ABS activate; additional examination between the groups was needed on future studies. Participants thought the 15 trials they had during the study was enough practice, the exercise was a practical tool, and they recommended the practice for new drivers, refresher training, as well as evaluating fitness to drive. The results from this study suggested that regardless of prior knowledge and experience with ABS, the emergency braking practice on the simulator is an effective tool for drivers to practice emergency braking with ABS feedback.

The eighth study (Chapter 10) aimed to understand if the emergency braking practice, the *Pedals Emergency Stop©* interactive exercise, had any effect on a driver's braking in a vehicle on a closed-road course. One group of participants completed the emergency braking practice on the simulator, which consisted of a practice with four trials, followed by three tests with four trials in each test. To pass the simulator practice, participants had to pass three out of four trials within a test. All participants completed a braking exercise on the track, where a professional driving instructor rated the participants' performance activating ABS using a behaviorally anchored rating scale with five ratings, where 1 equated to no activation and a rating of 5 corresponded to full ABS activation throughout the entire stop. All participants completed 5 runs at 35mph on the track. A total of 69 participants completed the study. Participants were grouped according to their prior experience feeling ABS activate as well as if they completed the emergency braking practice on the simulator or not, for a total of four groups. The results from the simulator portion showed that 94.7% of the participants passed the practice on Test 1 and every participant that passed Test 1 also passed Test 2 and 3. One participant passed during Test 2 and one participant passed during Test 3. The participant that passed during Test 2 also passed Test 3. The criteria developed to determine if a participant passed the emergency braking practice was found to be representative of the participant being proficient, regardless of an individual's previous knowledge and experience with ABS. The results from the braking exercise on the track did not reveal any differences in performance between participants that had completed the simulator practice and those who had not, nor were there any differences in performance between the participants who had and did not have previous knowledge and experience feeling ABS activate. The results of the study do not suggest any improvement in braking performance on the road for drivers who successfully completed the simulator practice, yet further investigation is needed due to a variety of possible confounds.

11.1 Future Applications

The emergency braking practice on the driving simulator with the *Pedals Emergency Stop*© interactive exercise, was reported on the surveys to be beneficial by the participants in Chapters 9 and 10. Future research should explore the *Pedals Emergency Stop*© interactive exercise to determine if the exercise is the most beneficial to novice teen drivers, who make up a disproportionate number of fatal crashes for their small percentage of the driving population (NHTSA, 2018b). The majority of teenage drivers' crashes can be attributed to driver error, which includes recognition errors (visual scanning errors, distraction), decision errors (following distance, vehicle speed relative to conditions), and performance errors (losing control; Curry, Hafetz, Kallan, Winston, & Durbin, 2011). The emergency braking practice on the simulator could help to address decision and performance related braking errors. Though there is not a requirement for all teen drivers to complete a driver's education course prior to the licensure exam, driver's education is commonly included in the graduated driving license process (NHTSA, 2017a). Integrating the emergency braking practice on the simulator with driver's education, may help novice teen drivers understand emergency braking as well as the haptic brake pedal feedback associated with ABS activation through the repetition of trials as part of the *Pedals Emergency Stop*© interactive exercise.

The automotive industry has been shifting to include technology that assists drivers and is moving towards self-driving, or vehicles with autonomous capabilities. This shift requires the vehicle to be able to take control of the steering, acceleration, and braking. To meet these demands, the future of braking systems will be focused on brake-by-wires systems. Brake-by-wire systems decouple the mechanical connection between the driver and the brakes, allowing for control of the brakes without input from the driver. This function is desirable as vehicles transition to higher levels of automation (SAE Level 2 through 4), where the vehicle assumes braking control (Kant, 2014).

One of the first brake-by-wire systems created was an Electro-Hydraulic Brake (EHB) system, which relied on an electronic actuator to measure braking input from the driver and the signal is then sent to the control unit that operated the hydraulic brake system (Stoll, 2001). Since there must be a failsafe in case of an electronic failure, the conventional, reliable hydraulic brake system served as the fallback.

DiamlerChrysler in collaboration with Robert Bosch created the Sensotonic Brake Control (SBC), which is an EHB system. SBC relied on highly sensitive sensors within the control unit, which integrated the wheel speed sensors utilized by ABS, and the sensors within ESC (yaw rate, lateral acceleration, and steering wheel angle) in order to electronically control the brake system (Stoll, 2001). Since the driver does not have a direct mechanical connection to the brakes in an SBC system, Mercedes-Benz researchers claim the haptic brake pedal feedback was eliminated. Simulator studies conducted utilizing the Mercedes-Benz driving simulator found that some drivers reduced brake pressure when they felt the haptic brake pedal feedback when ABS activated, which could lead to longer stopping distances. Researchers found a 57%

reduction in brake pressure when ABS was activated (as cited in Stoll, 2001). Though the simulator studies claim there was no feedback in the brake pedal, it is unknown if all of the feedback is eliminated in a vehicle and if there are variations in the amount of feedback based on the road surface or driving maneuver. SBC was included on 2003-2006 Mercedes-Benz E-class and CLS-class vehicles but was discontinued after various software issues with the system resulted in multiple recalls (Meiners, 2005).

Though conventional brake systems still dominate today's market, brake-by-wire systems will likely be utilized by future vehicles. The ability for autonomous technology to infiltrate the market will be determined by the willingness of users to accept the technology. Acceptance of a technology heavily relies upon trust (Lee & Moray, 1992), which is influenced by users' prior experiences and information received about the technology. Thus, users without experience and knowledge of the technology have minimal trust (Schoettle & Sivak, 2014).

Though brake-by-wire systems may eliminate the ABS brake pedal feedback, it is known that the rapid modulation of brake pressure can be felt through the entire vehicle as determined by the acceleration measurements referenced in Chapter 9 (see section 9.2.1.2.3.1 Measurement of ABS Brake Pedal Feedback in a Vehicle). Also, not all drivers have knowledge of and/or experience with ABS (Mims et al., 2020a; 2020b; 2020c; 2021) and the pedal feedback from ABS is not understood by all drivers (Mazzae, Garrott & Snyder, 2001).

In addition to the trend of increased automation, electric and hybrid vehicles will also utilize brake-by-wire systems. Electric and hybrid vehicles allow for regenerative braking where the energy during braking is captured and stored in the battery. Brake-by-wire systems are ideal for electric vehicles because they allow the distribution of braking energy between the friction brakes and regenerative braking. Due to the increased control with a brake-by-wire system, the braking feel is similar to a conventional vehicle (Hwang, Kim, Kim, & Jung, 2010). The driver will have a similar experience during emergency braking, where the brake-by-wire system eliminates the ABS brake pedal feedback, but the pulsation of ABS is felt through the entire vehicle.

As technology shifts focus to autonomous vehicles, the driving task will be eliminated and all individuals within the vehicle will become passengers. Future autonomous vehicle users may experience the feedback from ABS as passengers. If the user does not understand the feedback nor given information about what the feedback is doing, this could lead to the user losing trust in the autonomous vehicle. Future autonomous vehicles should consider the impact that ABS feedback could have on user trust and methods to provide information to users to help communicate that the feedback back is part of normal emergency braking operation.

APPENDIX A: SIMULATOR CONSTRUCTION

This appendix includes components necessary to construct for the novel driving simulator with haptic ABS brake pedal feedback as well as the instructions to assemble the aluminum pedal base.

1. Bill of Materials

Component	Quantity	Purpose
Fanatec ClubSport pedals V3 inverted	1	Pedals
Fanatec CSL DD steering wheel base	1	Communication to the pedals
CSL elite steering wheel	1	Initial setup of the pedals
ButtKicker Gamer2	1	ABS feedback
34" LG Class 21:9 UltraWide Full HD IPS Gaming Monitor	1	Monitor
Logitec speakers	1	Play sounds from exercise
Audio splitter	1	Split sound between speakers and ButtKicker
Logitec mouse and keyboard	1	For computer
Surge protector	1	Power connections
Rubber sheet V pattern	1	Rails on chair don't slide on floor
1.5"x3" t-slotted profile	196 in	Aluminum extrusion for chair rails and pedals support
45-degree support	1	Dead pedal
8-hole gusset corner bracket	3	Attach 80/20 together
4-hole tall gusset corner bracket	8	Attach 80/20 together
Bolt assembly	64	Attach 80/20 to gussets
1 hole strap 1/2" 4 pack	2	Hold chair to rails
Metal file set	1	File holes on chair straps to fit screws
Gorilla epoxy resin	2	Glue rubber to chair rails

2. Construction of Pedal Base and Chair Rails

The base that supports the pedals set is constructed using aluminum rails extruded in a t-slotted profile connected by a gusset.

2.1 Aluminum Extrusion Pieces

The aluminum t-slotted profiles must be cut to the designated lengths.

Length of t-slotted profile	Quantity
106 cm	2
83 cm	1
43 cm	2
30.5 cm	2
18 cm	1
13 cm	2
11 cm	1

2.2 Rubber Sheet Application

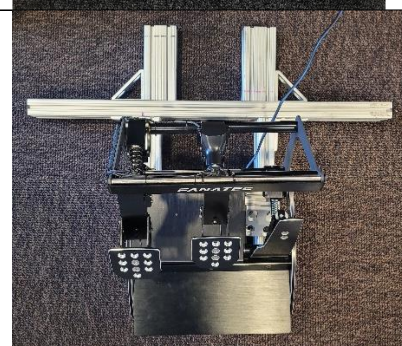
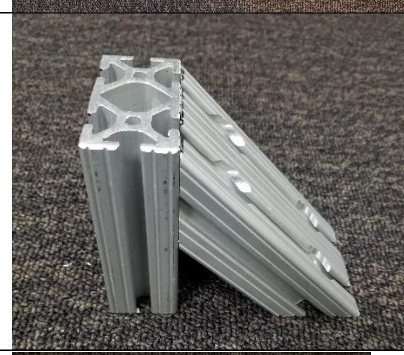
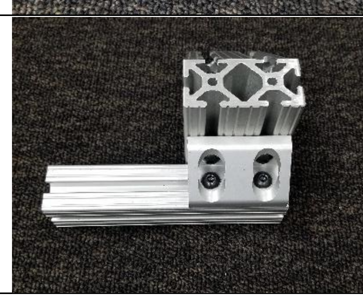
To prevent the aluminum t-slotted profile pieces from sliding across the surface of the floor when a driver is practicing emergency braking, patterned rubber is cut to size and fixed to the t-slotted profile pieces using the epoxy resin. Rubber was fixed to both 106 cm and both 13cm pieces on the 3in wide side of t-slotted profile. The rubber strips fixed to the 43 cm t-slotted profile pieces were to the 1.5 in wide side of the profile.

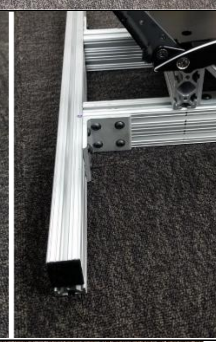


2.3 Assembly

To assemble the pedals support structure, begin by loosely attaching two of the 4-hole tall gusset corner brackets onto each 43 cm piece (rubber side down).

Step	Instruction	Image
1	Loosely attach two 4-hole tall gusset corner brackets onto each 43 cm piece rubber side down	
2	Connect both 30.5 cm pieces perpendicularly on top of the 43 cm pieces, where one 30.5 piece lines up with the ends of the 43cm pieces and the other 30.5 cm piece is 21 cm apart.	
3	Remove cover on pedals set to expose the feet with holes for attachment	
4	Line up the holes on the feet of the pedals set with the groves in the extrusion on the 30.5 cm pieces and secure with bolt assembly	

5	Ensure the hole on the back foot behind the clutch pedal is also aligned and secure with bolt assembly	
6	Measure 26.5 cm in from both sides of the 83 cm piece and lineup the 43 cm pieces perpendicularly, securing with 8-hole corner gusset brackets	
7	Attach two 13 cm pieces perpendicularly to the 83 cm piece (opposite of pedals set) 26.5 cm from the end	
8	Attach the 45-degree support to the 11cm tall piece using the bolt assembly	
9	Attach the 11 cm tall piece perpendicular to the 18 cm piece using a 4-hole gusset	

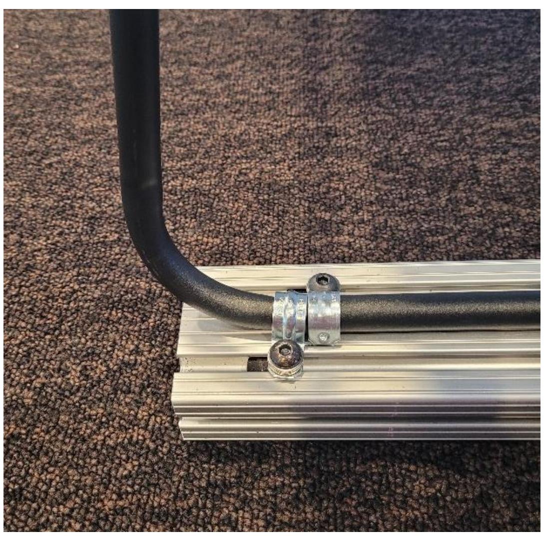
10	Attach the 18 cm piece to the clutch side of the pedals set onto the 43 cm piece		
11	Attach Velcro strips to the desk		
12	Attach Velcro to the ends of the 83 cm piece		 
13	Attach Velcro to the tops of the 13 cm pieces		

2.1 Chair Rails

To prevent drivers from tipping backwards while braking, The chair was mounted onto rails using one-hole straps and bolt assemblies.

The circular metal file is used to shave the holes on the one-hole straps so the bolts in the bolt assemblies fit.

One all eight one-hole straps' holes fit the bolts, place the chair so the chair rails are centered on the 106cm length aluminum t-slotted profiles. Attach two of the one-hole straps to the front of the chair rail using the bolt assemblies.



Attach two to the back of the chair rail and repeat on the other chair rail.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