Quantifying Drivers Foot Movements and Pedal Misapplication Errors

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Abstract

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Pedal errors refer to the situation when the driver mistakenly presses the wrong pedal or does not press the pedal at all. A negative outcome of pedal misapplications is a sudden acceleration event, which has been associated with crashes. However, there is currently little information on the specific contributions. The goal of this dissertation is to identify the factors associated with a higher likelihood of pedal errors through models of driver's foot movements. Data from 87 unique participants were collected from three studies: a driving simulator, parking lot study, and naturalistic driving. There were different foot trajectories observed that could be classified as a direct hit, hesitation, corrected trajectory, or pedal error. Within the pedal errors, four different sub-categories were observed: wrong pedal, slip, miss, and both pedals. These errors (3.27%) were not as common as the other foot trajectories and were therefore placed into one group for further analysis. Using a repeated logit model, pedal errors were shown to be

associated with age-related and situational factors, including the location of the triggered event. Further exploration of the driver-related differences in movements was conducted using a functional principal components analysis that showed that the largest contribution to pedal errors were observed early in the foot movement, when compared to the direct hit and corrected trajectory. Exploration of the situational context was further examined using a naturalistic study, which showed that turning maneuvers were less likely associated with errors as drivers had their foot on the brake pedal more often. The parking and start-up sequence also had an impact on the likelihood of a pedal error. Hence, a tight parking maneuver with a sudden event was also used. No pedal errors were observed in this study. But there were more braking events observed in the parking study when compared to a similar event in the simulator study. In summary, the series of study showed that an algorithm could be designed to detect a potential pedal error early in the foot movement process such that an alert could be provided to driver in a reasonable timeframe to allow correction of the movement. This dissertation describes the factors that can be considered for such an algorithm, and the process to identify these factors.

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CHAPTER 1. BACKGROUND

This chapter provides an overview of pedal misapplication issues and what research has been conducted to date. Given that this issue still exists, this dissertation strives to address some of the gaps in past studies using four research questions that are explained in greater details in this chapter.

1.1 Pedal Misapplication Issues

Drivers have identified issues associated with their vehicle accelerating unintentionally, suddenly accelerating, throttle sticking, engine surging, and excess idle speed since 1980 (Pollard & Sussman, 1989). In the past decade, the US DOT - National Highway Traffic Safety Administration (NHTSA) had received 15,174 complaints related to sudden acceleration (Green, 2010). Although some vehicles have been showcased more in the news, these incidents are not centered on any specific car manufacturer. They have included a 1970 Cadillac Eldorado suddenly reversed at high speed striking and pinning the pedestrian between the two cars (Mortimer, 2011); a 1988 Lincoln Town Car in Mountain Home, Arkansas, accelerated into a parking lot and hit two boys; and a car-washer employee in Albuquerque, New Mexico, was killed because a 2006 Jeep Grand Cherokee suddenly accelerated (Green, 2010), etc. Many vehicle manufacturers have experienced unintended acceleration, including Toyota, Ford, and Chrysler (Green, 2010). It is a challenge conducting research on this issue because oftentimes, the manufacturer and the driver cannot pinpoint the specific context associated with the unintended acceleration.

Over the past few decades, there have been investigations on possible causes due to the pedal design as well as electrical and mechanical defects, but nothing conclusive was ever observed (Schmidt & Young, 2010). Researchers provided several recommendations in improving the pedal systems, but pedal misapplications incidents still occurred and have even generated media attention (Wikipedia contributors, 2015). Given the low number of mechanical failures, researchers started investigating the driver's contribution to these crashes (Pollard & Sussman, 1989). Given that these cases are very rare, a few are presented for context.

Case Study 1: In September 2013, US DOT- NHTSA released a complaint report related to unintended acceleration of a Tesla Model S. The vehicle was going about 5 mph on a residential driveway. The driver complained that he was continually pressing the brake pedal but could not stop the car from accelerating. The vehicle accelerated to the road and finally stopped at a 4.5 foot high retaining wall. Tesla stated that it was shown that the accelerating pedal was pressed and that the car accelerated from 18% to 100% in a split second (Ireson, 2013).

Case Study 2: On July 16, 2003, an 86-year-old driver of a 1992 Buick LeSabre was following another car approaching an intersection in Santa Monica, Los Angeles County. The lead vehicle had begun to proceed when the signal turned green but it stopped again unexpectedly for pedestrians in a crosswalk. The elderly Buick driver mistakenly applied the pedal (accelerate instead of brake), and hit the stopped car and then raced out of control into a crowded farmers market.

Some of the unintended acceleration incidents occur due to human errors. The driver of the second case admitted that he might have confused the brake and accelerator pedals.

Some people have argued that some models may have mechanical defects, which have led to the unintended acceleration. NHTSA conducted an in-depth assessment to identify possible causes of unintended acceleration among vehicles that had the highest complaints (Lococo, Staplin, Martell, & Sifrit, 2012). The report concluded that the cause seemed more likely associated with human errors/pedal misapplications rather than vehicle malfunctions.

1.2 Previous Studies on Pedal Misapplications

When operating a vehicle, safety is impacted by many factors that change continually. Driver, environmental and vehicle factors have all been related to pedal misapplications. Previous studies in this area have been conducted based on a meta review of the literature, key word searches in crash reporting databases, and controlled studies using a driving simulator. The North Carolina State crash database and the National Motor Vehicle Crash Causation Survey (NMVCCS) have been previously examined because they contain narratives of the incident and pedal error related variables (Lococo et al., 2012; Schmidt, Young, Ayres, & Wong, 1997; Schmidt, Young, & Ayres, 1999). Other studies have used driving simulator to control for several factors (such as distraction, startled events, etc.) (Ivancic & Hesketh, 2000; Kimura & Shinohara, 2012). These simulator studies have been used in conjunction with video recordings of the drivers' foot movements (McCall & Trivedi, 2007; Tran, Doshi, & Trivedi, 2011).

1.2.1 Driver Factors

Age and gender

Studies have shown a relationship between crashes associated with unintended acceleration and drivers' age. Kimura and Shinohara (2012) showed that older drivers (mean age 66.2 yrs old) are more likely to make a pedal error when compared to younger drivers (mean age 21.4 yrs old). Lococo et al (2012) explored the factors associated with pedal misapplications using the investigative reports and the North Carolina State Crash Databases. He found that middle aged females (30 – 49 yrs old) and older (> 50 yrs old) drivers were overrepresented in the Audi 5000 sudden acceleration incidents when compared to other incidents nationwide (Lococo et al., 2012). Using the North Carolina State Crash database, Lococo (2012) observed a somewhat different trend, with younger (< 20 yrs old) and older (> 70 yrs old) drivers more likely involved in crashes associated with pedal misapplications.

Older drivers demonstrated more variability in foot movements when compared to young adults. This variability may have been the reason that there was a higher likelihood of older adults pressing the wrong pedal (Cantin, Blouin, Simoneau, & Teasdale, 2004). The mean and variance of the amplitude of their right foot movement were greater than those of younger drivers. The result might indicate a relationship between aging/variability in the lower limb movement and pedal misapplications.

The NASS crash database shows that fewer females are involved in all types of crashes when compared to males. However, females were over-represented in crashes associated with the Audi 5000 sudden acceleration events for the model years 1982 to

1987. The same phenomena was also observed in the study conducted by Lococo et al. (2012).

Body position and size

Head and body position as well as driver size may impact the drivers' ability to spatially position their foot on unseen pedals. Moving the head or eyes can cause large systematic biases in the targeted direction of the foot (Lococo et al., 2012). The bias could be large enough leading to missing or pedal errors. Thus, pedal misapplications were more likely to happen when driver rotated the body to see the rear of the vehicle during a backing maneuver. In the incident database (for example, the North Carolina database and the National Motor Vehicle Crash Causation Survey (NMVCCS)), such kind of accidents included people who looking or reaching to the side or rear of the vehicle, re-entering the vehicle quickly when the vehicle started to roll or while moving from one seat to another (Lococo et al., 2012).

Most vehicle seats are designed to fit 95% of drivers, however shorter drivers may not fit as well into the car seat (Hill & Boyle, 2006). Hence, the possibility of being involved in pedal error crashes is even larger for shorter females with smaller feet (Lococo et al., 2012) since they have to stretch using their toes, and usually need to pick their foot up to move between pedals.

Startled or panic

Pedal misapplications could happen during regular driving cycle, but might be more likely to occur when drivers are startled or panic. They perceive the sudden stimulus as life threatening, requiring an immediate solution (Schmidt, 1989). There might be a speed-accuracy trade off (Schmidt & Young, 1997): the likelihood of a pedal error increased when the driver was forced to respond more quickly. About 20% to 60% of pedal misapplication crashes in the police report database were described as startled or in panic (Lococo et al., 2012). Tomerlin and Vernoy (1990) examined the drivers' abilities to stop the car at backing maneuver when the vehicle suddenly ran at full throttle. Five subjects hit acceleration pedal in a hurry, and one of them never figured it out. Similar phenomena were confirmed by Pollard & Sussman (1989) and Schmidt & Young (1997) that some people responded much quicker but in the wrong direction during a startling event (Gielen, Schmidt, & Heuvel, 1983). Another interesting finding was that the number of crashes decreased as the driver age increased (Lococo et al., 2012) when the driver was startled or being panic.

Cognitive deficits

During sudden events, drivers need to analyze the environmental cues and recognize the need to process and plan a response and subsequently execute an action. Over time, this becomes a skill-based task. But in certain situations, it still requires drivers to make immediate judgments and decisions on unfamiliar events. When facing sudden events, different drivers might plan and carry out different decisions, which might or might not avoid the collision. Such abilities to respond to unexpected and sudden events were proved to be related to a person's cognitive function (Belanger, Gagnon, & Yamin, 2010). Cognitive impairment might also cause pedal errors that result in crashes or unintended accelerations.

Older drivers have a higher level of involvement in pedal error-related crashes given associated cognitive impairments. Cognitive impaired drivers (such as autism spectrum disorders (ASD), attention deficit hyperactivity disorder (ADHD), etc.) may have difficulties appropriately distinguishing the gas and brake pedals (Lococo et al., 2012). Freund (2008) conducted a study with three cognitive tests and a driving simulator, and found that certain cognitive tests could be used to predict pedal errors, such as the clock drawing test. The clock drawing test measures multiple areas of cognition function including comprehension, memory, visual-spatial abilities, abstract thinking and executive function, which could be used as the cognitive screening instrument (Shulman, 2000).

1.2.2 Pedal Design and Engineering Issues

Drivers distinguish pedals using sensory cues and spatial reference points since they are not able to see the pedals during driving. Although human errors play a large role in unintended acceleration incidents, vehicle design and engineering issues might increase the probability of pressing the wrong pedal(s) (Collins, Evans, & Hughes, 2014). According to Pollard and Sussman (1989), the possibilities of pedal errors increased due to the following characteristics of the vehicle pedal design: (1) relative close lateral spacing between brake and accelerator; (2) relative close vertical spacing between the two pedals; (3) similar feedbacks of pressing both pedals, which reduce the chances of recognizing; (4) engine torque exceed brake torque are allowed when both pedal are pressed simultaneously, and a powerful engine gives driver less time to make a correction.

Many researchers note that the way drivers position themselves in the seat and how they locate the pedals can be associated with pedal errors. In an unfamiliar vehicle, there may be a disruption to the driver’s postural set or orientation. Drivers unfamiliar with a vehicle are overrepresented in sudden acceleration incidents. Drivers who fail to adjust the seats and/or mirrors before driving are more likely to make pedal errors (Lococo et al., 2012). If a driver shifts to the right of their seat, he/she might mistakenly hit the accelerator pedal when the brake pedal was intended. Unfortunately, simulator studies failed to detect the relationship between pedal designs (for example, considering the vertical and horizontal spacing of the two pedals, and the distance between the right edge of the brake pedal and the steering wheel centerline) and pedal misapplications (Brackett, Pezoldt, Sherrod, & Roush, 1989; Rogers & Wierwille, 1988; Vernoy & Tomerlin, 1989) because pedal errors happened rarely.

1.2.3 Parking Tasks

With respect to environmental conditions, the majority of pedal misapplication crashes are reported to occur in daytime hours, in clear weather and on good road conditions (Lococo, 2012). Other situations where pedal misapplications can occur are during a parking or backing task (Young, Heckman, & Kim, 2011; Schmidt & Young, 2010).

Maneuvers associated with parking or backing tasks can include going straight ahead, and turning and slowing (Wu, Boyle, McGehee, Angell, & Foley, 2012). Parking or leaving a parking spot also require multiple foot movements and the driver needs to divide their attentions to different objects and events. While backing, the driver needs to look over their shoulders to ensure they are cleared to leave the parking space. Looking back can move the driver out of his or her regular seating position; hence increase the possibility of pressing the wrong pedal. Sometimes drivers have to look at the rear and the front of the vehicle simultaneously when trying to back into a parking spot. When their attention is divided, they may fail to consider their foot movement, and in a parked space, there is minimal room for correcting any pedal misapplication.

1.2.4 Foot Behavior

The pedal application is a skill-based motion conducted in an unconstrained space with no visual target and no feedback until initial pedal depression. Two important cues when operating the pedal are the pedal positioning and the "feel" (Pollard & Sussman, 1989). The direction and curvature of motion are critical and the feedback from touching the pedal (pressure, texture, shape or contour) is important for distinguishing pedal and foot placement. In the case of operating a pedal, the leg motion can be viewed as two degrees of freedom with free hip and knee joints.

Some studies examined the relationship between desired foot movements with muscle activity. Depressing pedals, for instance, requires repeated performance of muscular contraction with accurate force and timing. This human neuromuscular control system could be viewed as a multi-staged process in transforming sensory input into motor output through neural architectures (Shinsuk & Sheridan, 2004). Some investigators showed that human brains take dynamic properties of peripheral musculoskeletal system into account, and conduct the calculation to figure out all muscle activities in order to control the movement (Gomi & Kawato, 1996; Pennisi, 1996; Shadmehr & Mussa-Ivald, 1994).

Foot behaviors of normal braking were different from emergency situations, where the pedal misapplications were more likely to occur. Prynne and Martin (1995) showed that drivers exhibit a two-stage braking process when responding to emergencies and similar findings were shown in Ising et al (2012). In the first stage, the brake pedal is typically depressed to a moderate level; and in the second stage, the driver then brakes harder to achieve the deceleration needed in an emergency. Hillenbrand et al. (2005) proposed a collision prevention assistance system based on drivers' braking reaction for both normal and emergency braking.

Studies conducted by Park & Sheridan's (2004) showed that the trajectories of point-to-point foot reaching movements from young male subjects were fairly straight, with bell-shaped velocity profile. The result was consistent with an arm-motion studies (Flash, 1987; Mussa-Ivaldi, Hogan, & Bizzi, 1985). But more sub-movements were observed among elderly drivers when required to apply the brake pedal (Cantin et al., 2004). Kitazawa and Matsuura (2004) also showed differences in foot trajectory and velocity from the accelerator pedal to the brake pedal in response to normal versus emergency braking. The differences could be considered when developing a braking assistance system. But only a few participants (younger than 30 yrs old) were included in this study. These studies provided preliminary results on foot behaviors, but lacked a comprehensive statistical analysis for all kinds of pedal applications among different drivers.

1.3 Gaps in Literature

The existing police reports in most states in the US do not include the causes of the crashes. North Carolina is one of the few states that include the written narratives of the crash and is also accessible to the public. However, identifying the cause of a crash and selecting pedal misapplication related collisions based on the narratives is huge work. Minor crashes are typically underreported, so they are not represented in the police reports and additional information is needed to identify the context. Further, neither the earlier police report analysis nor the recent simulator/on-road studies takes a broad range of driver factors into account, including factors such as age, driving history, cognitive function and stature.

There are no studies that show how drivers position themselves into a car seat and how they determine if their foot is on the proper pedal. Two scenarios should be considered (Schmidt et al., 1999), parking or driving, when investigating foot behavior. Parking involves situations where the vehicle was in a parking lot, garage, or being parked in a parking space on the street. It was shown that pedal misapplications were more likely to happen when driver rotated the body to see the rear of the vehicle during a backing maneuver (Lococo et al., 2012). These previous studies on pedal errors have looked at the driving sequence in a forward only motion. These scenarios seldom consider the sequence of events that occur in a parking/backing scenario.

Pedal errors are rare events but might lead to serious damages and injuries. Challenges are presented when capturing the rare pedal error events on-road and even in controlled experiments. Further, the examination of pedal errors requires an understanding of the temporal and spatial nature of the data. The proposed methods, as part of this dissertation attempts to address these issues.

1.3.1 Considering Efference copy and Simon effect

There are two phenomenon described in the psychology literature that may provide some insights to why pedal misapplications occur. One is efference copy and the other is the Simon effect. Efference copy was first introduced by Charles Bell (1823) and

Johannes E. Purkinje (1825) and referred to the visual perception or sensorimotor coordination (Bridgeman, 2007). After that, efference copy was shown to affect perception physiological motor control and could be used to correct errors of movement (Christensen et al., 2007). In general, a predictor uses an efference copy of the motor command to forecast the consequence of a certain behavior. The central nervous system tries to compare the behavior of the body and the predicted results (Wolpert & Flanagan, 2001). If the actual feedback matches the predicted consequence, the person might conclude that there is no error during this process. However, when human brain attempts to predict the body's motion/response but the prediction does not match the external perceptions, a circling/modulating behavior will be observed (Wolpert & Miall, 1996).

Schmidt alluded to the issue that efference copy was related to pedal misapplications (Schmidt, 1989) but no further studies discussed this effect in driver behavior. Figure 1 shows how sensory systems are adjusted according to predicted feedback by motor output. The driver intended to press the brake to respond to certain situations (such as a red traffic signal), and the brain make a command that the right foot should press the brake pedal. The brain, at the same time, also predicted the feeling of pressing the brake pedal. If two pedals generated similar feedbacks, no difference could be detected in the predicted and actual feedback. That said, the driver might believe that he/she pressed the correct pedal even though he/she made a mistake in reality. An efference copy might substitute the actual feedback from the foot with the predicted sensory feedback.

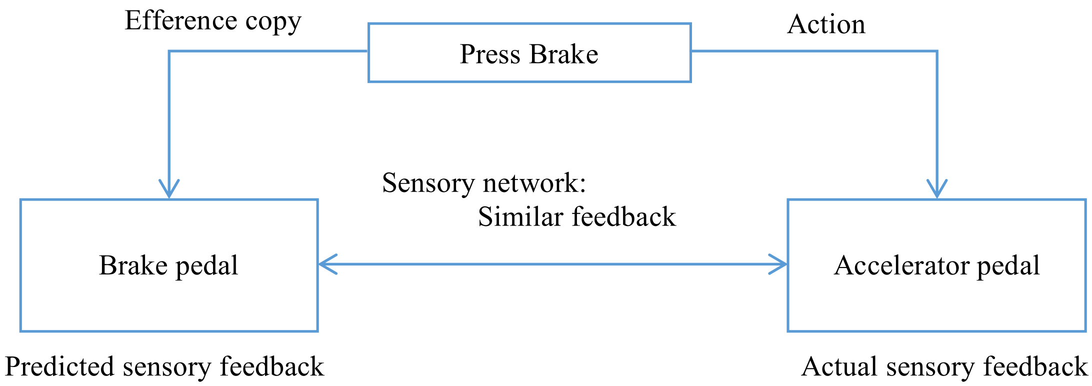

Figure 1 Sensory system adjusted according to predicted feedback

The Simon effect refers to the phenomenon that reaction time is shorter if the response corresponds spatially to the stimulus, even though the location is completely irrelevant to the tasks (Hommel, 1993; Simon, 1969; Sokolov, 1963). The stimuli (either in different colors or shapes, or both) could occur at either the left or right to the participants and the location of the stimuli is irrelevant in deciding the response. The participants are to press one of two response buttons/keys to indicate where the stimuli appeared. Craft and Simon (1970) showed that the stimulus indicating the right response elicited a quicker reaction when it appeared to the right of the participants.

In general, the brake pedal and accelerator are both operated by the right foot, and the accelerator is placed to the right of the brake pedal. Pedal layouts are slightly different across different makes or models and have been improved in the past decades. With respect to the Simon effect, responding to a traffic signal is a task in which the driver has two ways to respond: pressing the brake pedal on the left or accelerator pedal on the right. Thus, shorter reaction times would be expected when responding to a green signal on the right hand side, since the gas pedal is on the driver's right hand side. Similarly, a red stimulus occurs to the right hand side of the driver, which requires the braking action, might generate longer reaction time. In reality, such events require a very quick response but psychologically take longer time for the driver to figure out which pedal to press. As a consequence, the drivers might miss the perfect time to react or they are so panic that they press the wrong pedal.

1.3.2 Modeling pedal misapplications

Pedal misapplications are not easily quantified based on a snapshot in time. There is currently no standard description or definition of pedal error types. Most statistical models in the behavioral sciences do not capture the temporal and spatial differences that are inherent in pedal studies. Pedal movements require an examination of the differences in trajectory between those who have done it correctly and those who have not. Further, it is quite probable that a driver who is likely to misapply the pedal, will do it repeatedly and these within subject variations need to be accounted for in the model.

Previous studies have only classified and studied the pedal errors in a few ways (Table 1). To summarize, four or more different sequences are possible when pedal errors happen:

- An error occurred – it was detected – it was corrected – no crash occurred
- An error occurred – it was detected – it was not corrected – it resulted in (or contributed to) a crash with a known (identifiable) cause
- An error occurred – it was not detected – it was not corrected – it resulted in (or contributed to) a crash – and the driver blamed the vehicle

- An error occurred – it was not detected – it was not immediately corrected – but happened in a benign setting where no crash or adverse consequences resulted

Only errors have been classified and there could be more types of pedal errors. Correct movements are equally important to ensure that the outcomes are appropriately compared.

Table 1 Summary of Pedal Response Classifications in Previous Studies

Authors	Classification	Type of Data
Tran et al. (2011)	Misses or misapplications	Vehicle experiment
Schmidt and Young (2010)	Slips and wrong pedal	Crash data
Young et al. (2011)	Slip and miss errors	Crash data
Rogers and Wierwille (1988)	serious, catch and scuff errors	Simulator study

Very few studies have analyzed drivers' foot behavior (Tran, Doshi, & Trivedi, 2011). Of these, some have used video cameras to capture drivers' movements, but none have analyzed the entire procedure of a pedal application. All have focused on predicting drivers' intent to press the pedal(s). Some of the more promising techniques used include functional data analysis, motion detection and Hidden Markov Model. For example, Chaffin, Faraway, Zhang, & Woolley (2000) conducted a functional data analysis for the drivers' right-arm reaching motions. Tran, Doshi, & Trivedi (2011) analyzed and predicted driver foot gestures based on the foot states (such as "move towards brake/accelerator", "brake/accelerator engaged" or "release brake/accelerator") using the optical flow based foot tracking and Hidden Markov Model. McCall & Trivedi (2007) predicted drivers' braking action (whether there is a need to brake and whether the driver plan to do so) with information collected from the vehicle, surrounding environment and the driver's foot positions around the pedal. Although pedal trajectories are somewhat hard to quantify, the idea of capturing the 3-D space is promising.

1.4 Research Questions

There are four research questions for this study. It is of interest to study drivers' pedal response categories (direct hit, hesitation, corrected trajectory and pedal error) and the factors associated with those categories. A functional principal components analysis is useful to visualize the major contributions to pedal errors and to identify the common patterns associated with pedal applications. Exploration of the situational context is further examined using a naturalistic study, which included additional variables associated with the driving sequence as well as other drivers' characteristics. As different foot behaviors were observed for emergency braking event, the fourth research question summarizes and quantifies the drivers' response towards emergency events.

Research question 1: Do different traffic signal cues impact foot behavior? Video data from a driving simulator will be used to examine pedal application types (direct hit, hesitation, corrected trajectory and pedal errors). The initial hypothesis is that the type of pedal application types will be impacted by the driver and situational factors. Different foot behaviors will be identified and modeled using statistical models with repeated measures. The outcomes are described in Chapter 3.

Research question 2: What variations exist in drivers' foot-to-pedal behavior? The goal is to assess the most common movements for pressing the pedal(s). This question is examined using information from a simulated environment where the variations in drivers' foot trajectories towards the pedal can be captured. Functional principal components analysis is used to identify where the most variation occurs for the various pedal application types. The outcomes are described in Chapter 4.

Research question 3: Does foot behavior differ in terms of context and driver characteristics? This research question is addressed with data collected on-road using the driver's own vehicle. Foot placement on the pedal(s) and the pedal application types are summarized from the video data. Similar strategies of categorizing pedal applications (as defined in RQ1) are applied, and then a random forest is used to predict the pedal application categories given the greater number of features that were obtained in a naturalistic setting. A mixed logit model was then used to predict foot placements. The outcomes are described in Chapter 5.

Research question 4: How do drivers respond to emergency events? Previous studies have shown differences in drivers' behavior in normal driving and emergency situations. The sample size available to address this question was fairly small as these events are rare in the real world. Hence, summary statistics are generated as an exploration of drivers respond to emergency situations within a driving simulator, in a parking scenario, and in a naturalistic environment and inferences are provided for future research. The outcomes are described in Chapter 6.

1.5 Summary

This chapter provided an overview of unintended acceleration. Pedal error refers to the foot behavior that the driver pressed the wrong pedal or failed to press the correct pedal, and appear to be associated with many unintended acceleration crashes. Although pedal misapplications are considered rare events, the consequences can be severe.

Previous studies showed that factors associated with pedal errors include the driver, driving tasks, vehicle design and engineering issues, and the surrounding environment. Gaps in literature and the study objectives were discussed at the end of this chapter. The experimental design will be discussed in the next chapter and the following chapters present the data analysis. The last chapter describes some of the more interesting findings, study limitations and future work.

CHAPTER 2. METHOD

Previous studies show that pedal misapplications can be observed for various driving tasks (while driving forward, back or parking). Hence, a comprehensive set of studies was conducted to examine pedal application for various tasks. Differences in drivers were captured using standard demographic information as well as a battery of cognitive function tests and anthropometric measurements. The study is divided into two parts: (1) a controlled study using a lab-based driving simulator and an instrumented vehicle in a parking lot; (2) a naturalistic driving study to observe drivers' real world driving behavior.

2.1 Driving Simulator Study

The driving simulator study was designed to purposely overexpose drivers to pedal misapplication situations. Given that pedal misapplications are rare events, repeated scenarios are used to identify the likelihood of these situations. It was surmised that the ability to switch between responses is an executive function that has the closest relationship to pedal misapplications. Tasks that require switching of responses might impair human performance (Gilbert & Shallice, 2002; Philipp & Koch, 2005) and depending on the most recent events, the likelihood of a pedal misapplication could increase (Doshi, Tran, Wilder, Mozer, & Trivedi, 2012). Furthermore, according to Lococo et al. (2012), most errors occur when the driver's foot transitions from the floor towards the pedal(s). In an actual traffic environment, drivers need to respond to the color of the traffic signal (red, green or amber), which becomes routine with more skill-based processing. That said, the driver might face situations where the signal transitions to another color at an unanticipated time. The proximity of the traffic signal can affect the quickness of the drivers' pedal decisions and any hesitation may result in severe consequences (Doshi et al., 2012). There could also be significant differences in the mounting of traffic lights given various road types; traffic lights could be mounted on poles situated on street corners, hung over each lane of the road, or installed in the middle of an intersection. Thus, it is possible that different pedal applications may occur depending on the traffic light locations. That is, the external environmental could potentially influence drivers' pedal applications.

2.1.1 Apparatus

During the first part of the study, the vehicle will be integrated into a modified hybrid fixed-base non-driver in the loop simulator. The 2012 Toyota Camry XLE is used within a hybrid simulator garage bay, and secured in a stationary position. The foot pedals, transmission, and engine are decoupled from the vehicle control during this portion of the study. Sensors will be installed to record all pedal presses. These data will be recorded on the central computer located in the trunk. A 70" screen will be mounted over the hood of the car, on which the driving scenario will be projected. Three footwell cameras will be installed to acquire video of foot movements on the pedals. In addition, cameras will be installed to acquire video of the forward view of the driving scenario, and video over the driver's shoulder. A video camera will also be positioned on the driver's face. All of these will be multiplexed and synced with other data, including the data from the driving simulator. A special pre-ignition instrumentation plus the main data acquisition system will make sure that data acquisition will begin at time of door opening, and will continue through "ignition" till the end of the experiment.

2.1.2 Experimental Design

The scenarios (Figure 2) used were based on a previous study conducted in Japan (Abe et al., 2012) and include traffic around the participant's vehicle that moved at a moderate level of service. Horizontal traffic signals included red, amber, and green phases (Figure 3), and the traffic signal could be located in the left, middle or right of the center lane. The drive encompassed 78 green traffic phases, 9 red phases and 7 yellow phases (for a total of 94 phases). Participants were not told the number of green, red, or yellow phases included in the study. The signals appeared at varying lengths of time ranging from 0.76 to 1.13 seconds (median=1.04 s). The time interval between the two signals ranged from 0.33 to 2.30 seconds (median=0.53 s). At the very end of the drive, a vehicle pulls out from the driver's right side and merges into the driver's lane, directly in front of the driver. Immediately after viewing the 91st signal, this lead vehicle will brake abruptly forcing the driver to respond (Figure 4). The focus of this study is on the driver's immediate pedal responses to events such as the red and green phases of the stimuli and the sudden braking event.

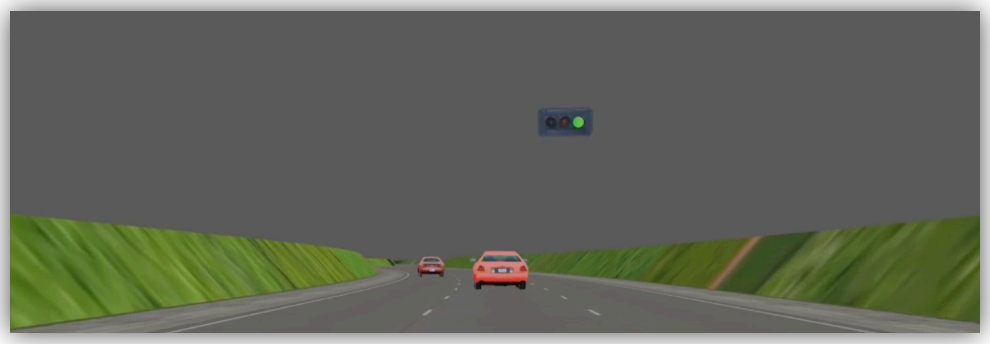

Figure 2 Example of simulator road

Figure 3 Signal Light States

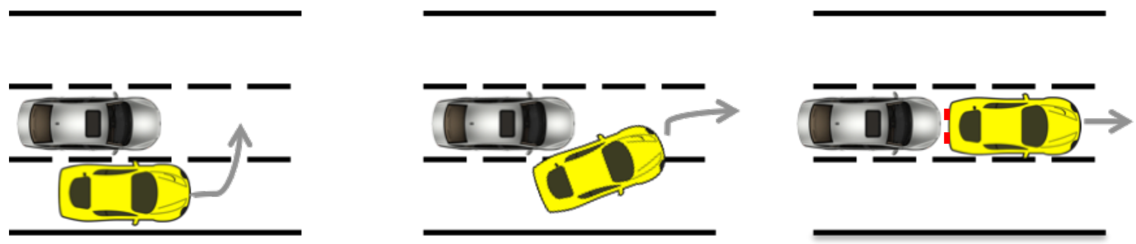

Figure 4 The lead vehicle braking event (with participant's the car in the middle lane)

Kimura and Shinohara (2012) conducted a similar pedal response task using colored stimuli. The road condition (3 lanes in one direction) was similar to Doshi, Tran, Wilder, Mozer, & Trivedi (2012) but their traffic signals would appear in the same location. In this current study, the signal varied across the three lanes and may appear closer or further from the participant. That is, the signal appears to be closer if the signal is larger in size on the projection screen, and further away if the signal is smaller. The modification is used to address our research question related to differences in foot behavior given traffic signal locations. Only one road type was used since Ising et al. (2012) showed that road condition was not a significant factor related to the delay in driver's response.

The simulated environment was set up to be in "adaptive cruise control" mode and the vehicle "steered" itself in the middle lane of the highway. In other words, the scene would move toward the driver at a predetermined rate. This scenario was used given the findings of Abe et al (2012) that showed no differences in steering angle and lane deviations among drivers in a study on pedal operation.

2.1.3 Procedures

After arriving, each participant was given an informed consent form and administered a questionnaire. Then they were invited to get into the driving simulator and were asked to position themselves comfortably, just as they normally would to drive. There was a 2-minute practice driving to help them get familiar with the driving simulator and the scenario. There was a very brief checklist that was used to determine whether participants are developing early signs of simulator sickness. This checklist was given at several points during the simulator portion of the study. When finished, they were invited to exit the vehicle, and were given a mid-study questionnaire (inviting them to rate the comfort of the vehicle interior). At the same time, the experimental staff recorded several aspects of the seated position the driver used within the vehicle during the simulator drive: the position of the seat on the seat-track, seatback angle, and steering wheel tilt angle (the driver will be asked to leave this as they were when they exit the vehicle). At this point, anthropometric measurements were taken. Elements of stature and body size would affect drivers seated positions and their reach/use of the pedals. After that, participants were given the neuropsychological test (Brain Baseline Assessment).

Simulator Driving Procedure

Drivers were asked to respond as rapidly and accurately as possible in response to several traffic signal phases. Their pedal selection is based on the following signal states (Figure 3):

- If the light turned green, they were to press the accelerator pedal
- If the light turned amber, they were to do nothing
- If the light turned red, they were to apply the brake pedal

During the "null" state (in between signal lights) the driver was instructed to place both feet on floor pan (and drivers were instructed to return their feet to this position following each foot pedal response).

Neuropsychological Test

Driving performance was proved to be associated with individual neuropsychological test scores (Anderson, Rizzo, Shi, Uc, & Dawson, 2005; Freund et al., 2008). In our study, neuropsychological test consisted two Trail-making tests (A & B versions). This test was a test of speed for attention, sequencing, mental flexibility, visual search and motor function. They will be administered using Digital Artefacts' "Brain Baseline" software on the iPad (http://brainbaseline.com/). In brief, in the Trails Test, participants must perform a task that is similar to a "connect-the dots" task. In the Trails A version, they trace a connection between numbered circles, in order (1 – 2 – 3, etc.). In the version called Trails B, they trace a line that alternately connects numbered and then lettered circles in order (1 –A - 2 – B – 3 – C, etc.). The performances were measured as the number of errors, restarts and total time used in each trail.

2.2 Parking Lot Study

In the parking lot study, the driving scenarios took place outside in a closed parking lot. This study was designed to examine drivers' pedal use in a backing and parking task in low speed associated with lots of pedal activities. During the backing task, drivers rotated their body to look at the rear and their attention might be divided. Such situation could increase the chance of making a pedal misapplication. As pedal misapplication might be more likely to occur when the drivers are startled or panic, this study also included one sudden event to capture the most natural response from drivers.

2.2.1 Apparatus

During the second part of the controlled study, the same instrumented vehicle, 2012 Camry XLE, was used. At the beginning of the study, the vehicle was properly positioned and parked in the starting position for the parking lot scenario. All other instrumentation will remain in the vehicle, including the special pre-ignition instrumentation, and will continue to function in the driving scenario that is conducted in the outdoors parking lot.

2.2.2 Parking Scenario

The driving scenarios took place outside in a portion of a closed parking lot (Figure 5) that have been designed to examine phases of pedal use in low speed maneuvers associated with parking (both pulling in and backing out). The parking lot scenario consisted three sub-phases: (1) Entry into the vehicle, driver positioning, and vehicle startup (at start position A), (2) the "Move-the-Vehicle Scenario" (back the vehicle into position B) and (3) a tight Pulling-in Parking Maneuver (park the vehicle in position C). The participants were asked to back up and pull forward several times until the vehicle was positioned in the space satisfactorily. During the study a "startle" event occurs as the participants near the boxed parking spot when they are almost parked into Position C. The startle event will consist of the sudden-onset of a vehicle's horn alarm from the driver's own vehicle. It has been observed that this type of startle or distraction might cause some momentary pedal confusion.

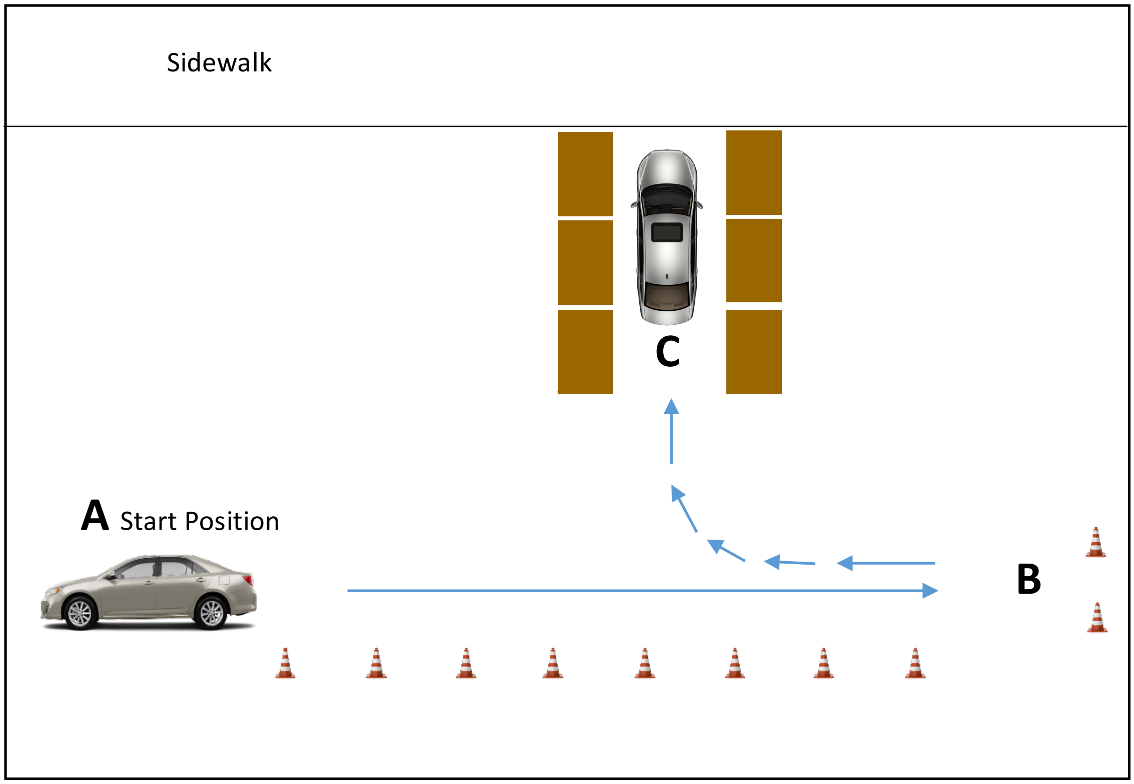

Figure 5 Parking Lot Scenarios

2.2.3 Procedure

After a short break followed by the driving simulator study, the participant was escorted outside the lab to begin the parking lot maneuvers. Instructions about the parking task were given, and then the participant started to move the vehicle from the parking space into another parking space (which will be pointed out to them). They could exit the vehicle once they finished parking. A post-study questionnaire was the final step for them to complete.

Parking Procedure

1) <u>Entry into the vehicle</u>

These began with the participant entering the vehicle, which was parked and stationary (ignition off) in Parking Spot A. The driver entered the vehicle, then adjusted the seat and mirrors and fastened the seat belt. Directions of the study were given before the participant starts to move the vehicle.

2) Move-the-Vehicle maneuver

The driver needed to move the vehicle out of the original parking space (A) and backed to Position B in this step. The backing camera was turned off so the participants were instructed to look over their right shoulder during backing (in other words, do not use side mirrors). There was a line of lane delineators that create an artificially narrow lane to back in.

3) Tight parking maneuver

The parking spot was very narrow, so the driver must “jockey” (back-up – move forward – back-up – move forward (approximately 3 to 4 times)), which requiring lots of pedal activities and torso turns. The startle event would be triggered when the participant almost parked the vehicle into the tight parking space.

Parking spots were lined along the sides with empty boxes (e.g., refrigerator boxes that were anchored at the bottom so they will not tip over). There would be no damage if the boxes were hit inadvertently. But drivers should be careful to avoid hitting anything on the way out of or into the parking spot. If they hit anything during the study, they had to start over. If, after three attempts, the participant was unable to complete the task without hitting the boxes, the participant would be dismissed from the study and replaced.

2.2.4 Participants

Email invitations and web announcement were used to invite participants. Participants were screened using the standard health screener normally applied for driving research at the University of Iowa to ensure that each participant was free from any serious health issues that would place them at risk during the study, and was licensed to operate a motor vehicle. Eligible participants must also be willing and able to refrain from the use of alcohol or medications that would interfere with driving for a period of 48 hours before their scheduled appointment for participation.

There were 62 drivers that participated in the driving simulator and parking lot study. Due to drops outs (those who did not or could not complete the entire study) and equipment malfunction, only 44 participants had valid driving simulator data for the forthcoming data analyses. There were 57 participants with good data for the parking task. Participants who finished the study were compensated $40 for their time and effort. Table 2 shows the demographic statistics of these participants included in this study.

Table 2 Distribution of Participants by Age and Gender

	Expected		Actual simulator		Actual parking	
Age Group	Male	Female	Male	Female	Male	Female
18 – 19 years old	5	5	5	5	5	5
25 – 44 years old	5	5	1	6	6	6
45 – 64 years old	5	5	5	4	7	6
65 – 74 years old	5	5	4	4	6	5
75 + years old	5	5	5	5	6	5
Total	25	25	20	24	30	27

2.3 Naturalistic Driving Study

Some instrumented vehicles were used in naturalistic driving studies recently (Dingus et al., 2006; Hickman, Hanowski, & Bocanegra, 2010), which made it possible to collect information on real world driver behavior. Such systems usually equipped with sensors and cameras so that the researchers would be able to rebuild and understand the complex circumstances and situations after the experiment. This current naturalistic driving study would be able to observe all kinds of driving tasks under variety of weather and road conditions.

2.3.1 Apparatus

The naturalistic driving suite was developed by Digital Artefacts Video Event recorder (DAVEr). This system includes a palm-sized device that integrates two video cameras (forward and interior view), two foot well cameras, a three-axis accelerometer, GPS, cellular modem and LG card, a 20-second data buffer, two infra-red illuminators (lighting the vehicle's interior and foot well at night) and a wireless transmitter. The main recording device was mounted on the windshield behind the rearview mirror. This box captured audio and video from both inside and outside the vehicle. The cameras were placed in similar locations in different vehicles to capture the accelerator pedal, brake pedal and the heel of the driver. They were located in areas that did not interfere with driving. Figure 6 shows views of the DAVEr installed in a vehicle and Figure 7 shows a sample view of video.

Figure 6 DAVEr installed in vehicle

Figure 7 Video Views Captured by DAVEr

2.3.2 Experimental Design

Complex traffic situations and more realistic driving were considered in this phase of study. GPS, accelerometer and on board diagnostic data were collected continuously. As pedal misapplications are more likely to be associated with the brake pedal or at low speed, video data would be recorded at the start and end of each drive, at crashes, and at accelerometer threshold settings of 0.6 g or greater.

- *Startup sequence:* The system booted up within 3-6 seconds after the driver's side door was opened and recorded for one minute or until the vehicle's speed reached 20 mph whichever came first.
- *Parking sequence:* The system recorded the last minute of drive going back from vehicle ignition being turned off.
- *Longitudinal trigger threshold:* The force level required to trigger the system with a positive or negative acceleration. Longitudinal triggers are most often caused by hard braking. The threshold setting used for this study was ±0.6g.
- *Lateral trigger threshold:* The force level required to trigger the system with a lateral acceleration. Lateral triggers are most often caused by hard cornering or swerving. The threshold setting used for this study was ±0.60g.

2.3.3 Procedures and Participants

This study started the existing choice response study in previous study (driving simulator study) and followed with a naturalistic driving experiment. The neuropsychological assessments, measurements of anthropometric dimensions and the driving simulator study were exactly the same as those in the previous controlled study.

After interested participants passed a phone screening, the year, make, model and trim level of their vehicle were recorded and emailed to NADS. The vehicle's electronic configuration reviewed the information to ensure the compatibility with DAVEr system. If the vehicle was compatible, participants would be scheduled for a two-hour visit for system installation and the simulator task.

Upon arrival, each participant was given a consent form and vision tests. Then subjects would sign a video release form, complete a demographic questionnaire and neuropsychological assessments. Then, participants would be taken to the driving simulator and asked to position themselves comfortably in the vehicle cab, just as they normally would to drive. At that point, the participants completed a practice session and then the driving simulator study trail. The measurements of anthropometric dimensions were recorded after the simulator driving.

At the same time, the DAVEr system would be installed in the participant's vehicle. Measurements and photographs were recorded for the brake and accelerator pedals. Additional features were recorded such as the type of pedal (rubber, metal) and level of wear on the pedal.

- Brake pedal: Measure length, height, width
- Accelerator pedal: Measure length, height, width
- Horizontal Separation (edge to edge): Measure from the left edge of the accelerator to the right edge of the brake
- Horizontal Separation (center to center): Measure from the center of the accelerator to the center of the brake
- Vertical Separation: Measure from the normal to the plane of the pedals.

All the information were used for installing the DAVEr system and the participants would receive instructions about the system. Once installed, the system would be triggered under situations discussed above and video and sensor data will be recorded.

All data were encrypted and automatically uploaded to DA server on a daily basis via a secure cellular connection, usually between 2 AM and 3 AM. Once downloaded, the encrypted data were filtered to remove invalid triggers such as bumps. The data were then compiled for coding. Approximately 4 weeks after the install, participants returned for 1-hour system removal visit at the NADS. No other procedures would take place on this visit.

A total of 30 participants were drawn from two age groups: drivers age 25-35 years (n=10) and drivers over the age of 65 years (n=20). An attempt was made to balance by gender; however, due to some subjects' habit of braking with the left foot, the final sample included two more females than males. Selection criteria for eligible participants in this naturalistic study were similar with those in the controlled study: healthy, licensed drivers, had proof of vehicle insurance, and drive, on average, at least one round trip per day. The participants' vehicle must have an automatic transmission, be free of special equipment (pedal extensions, hand brake or throttle or spinner wheel knobs) and have a model year of 1996 or newer. Eligible participants were asked to refrain from the use of alcohol or medications that would interfere with driving for a period of 24 hours before their scheduled simulator appointment.

2.4 Summary

This chapter gives an introduction about the experiments design (driving simulator, parking lot and naturalistic driving study) and the procedures. Pedal misapplications were examined in several different situations: driving simulator, parking tasks, and naturalistic driving. The purpose of this research is to study the factors that might influence driving performance and cause pedal misapplications. Related variables include demographic information (such as age and gender, cognitive function levels and anthropometric measurements), foot behavior (such as reaction time, pedal response) and situational variables (for example, traffic signals, startle events) and will be used in the following analysis.

CHAPTER 3. PEDAL APPLICATION TYPES

This chapter explains how the different pedal application types were identified. These pedal application types were then used in a logit model with repeated measures to estimate the likelihood of conducting a specific pedal applications type. The model considered drivers' characteristics, situational variables and other patterns associated with pedal misapplications using the hybrid-driving simulator (described in Chapter 2). The main research question addressed is: Do different traffic signal cues impact foot behavior? This is addressed in two sub questions: (1) Do differences exist in foot behaviors given traffic signal color and location? (2) If differences exist, what factors are associated with a higher number of pedal errors? The findings of this chapter have been accepted for publication in Journal of Human Factors and Ergonomics (Wu, Boyle, McGehee, Roe, Ebe, & Foley, 2015).

3.1 List of Variables

3.1.1 Independent Variables

In the driving simulator study, data for 43 subjects (20 males, and 23 females) were used in the forthcoming analyses. The experiment included two between-subject factors: age group (4 levels) and gender (2 levels), and three within-subject factors: signal color (2 levels: Green and Red), signal lane position (3 levels: Left, Middle and Right), and signal distance (2 levels: Further and Closer). Drivers' age and gender are included in the analysis given prior associations with pedal error incidents (Lococo et al., 2012). Participants were grouped into four age groups: young (< 21 yrs old, n=10), middle age (26 – 55 yrs old, n=14), older (60-74 yrs old, n=9) and oldest (≥ 75 yrs old, n=10). Older drivers may have more variability in foot movements when compared to young adults (Cantin et al., 2004) and it was of interest to explore whether this greater variability would increase the likelihood of a wrong pedal press.

3.1.2 Dependent Variables

Three variables are used to quantify foot behavior: pedal application types, reaction time, and pedal duration time. Pedal applications were classified based on video analyses of the trajectory of foot movements. In total, there were three classifications of correct pedal placement and four classifications of incorrect pedal placement (or pedal errors) identified (Table 3). In most cases, the participant would press on the correct pedal in a straight movement (Direct Hit). Other times, some hesitation was observed. A pedal movement was classified as hesitation if the participant's foot hesitated for at least 100 ms before any action took place (Doshi et al., 2012).

Table 3 Classifications of Pedal Applications

Pedal	Classification	n	Description
Correct Pedal	**Direct hit**	3,266	The participant pressed the correct pedal in a straight movement (without any hesitation and change in direction) when the signal light appeared.
	Hesitation	150	The participant's foot waited for at least 100ms (compared to direct hit) before moving the foot toward the correct pedal
	Corrected trajectory	224	The participant moved their foot toward either pedal and then needed to change the movement before stepping on the correct pedal
Incorrect Pedal (or Pedal Error)	**Incorrect trajectory**	44	The participant directly hits the incorrect pedal or the participant changes his/her foot movement before stepping on the incorrect pedal.
	Miss the task	2	The participant did not respond to the traffic signal
	Miss the pedal	9	The participant tried to reach a pedal but failed to touch on the correct pedal.
	Slip	46	The participant touched the pedal but his/her feet slipped from the correct pedal.
	Both pedals	22	The participant touched both accelerator and brake pedals at the same time using one foot.

The foot toe position was plotted based on the video data using the motion detection technique discussed in Chapter 3. Figure 8 shows examples of the foot to pedal trajectories for different pedal application types for only one participant. The positions were plotted (in pixels) based on the two-dimensional (2D) camera view. The very left end point in each plot identifies when the participant depressed the pedal. The "direct hit" typically has the highest touch point, while "miss" has the lowest. For example, the participant in Figure 8 depressed the pedal at coordinates (385, 270) for a direct hit, and at coordinate (381, 205) when there was a miss. In general, movements that had an ending point larger than 250 pixels was associated with a successful hit on the pedal. However, if the end point was lower (i.e., closer to 200 pixels), then the trajectory might result in a slip or miss.

Figure 8 does not show an "incorrect trajectory" or "both pedals", but the paths are similar to a "direct hit" except that the participant would directly hit a wrong pedal or two pedals. There were very few incorrect pedal placements classified as incorrect trajectory (n=44), miss the task (n=2), miss the pedal (n=9), slips (n=46) or touched both pedals (n=22). Therefore, these five types were combined for the forthcoming analysis.

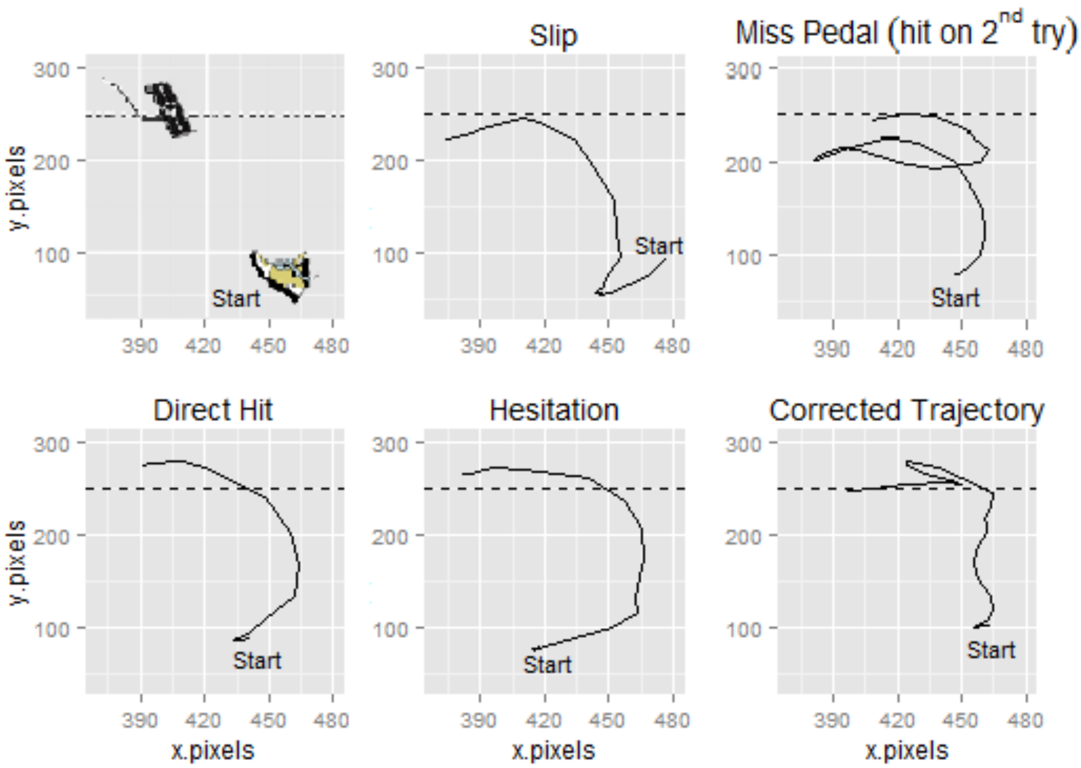

Figure 8 Examples of the foot to pedal trajectory for each pedal application type for only one participant (dotted line represents the vertical middle position of the brake pedal).

Pedal response time was computed from the time that the traffic signal appeared on the screen to the moment the participant touches either pedal. Pedal duration is computed as the total time the participants' foot was on the pedal and included the time any pressure is detected on the pedal to the time when pressure is no longer detected. The combination of the response time and the pedal duration is used to describe the pedal application process. These two variables were examined and considered in the context of the four application categories. Response time may be quicker for different types of foot movements/categories. Alternatively, some drivers might continue to press a wrong pedal for a longer time given the signal color.

3.2 Statistical Models

A mixed effects multinomial logit model (MMNL) was used to predict the likelihood of a pedal application being in one of four categories: Direct hit (baseline), Corrected Trajectory, Hesitation and Pedal Errors. The explanatory variables (or independent factors) included in the model were age, gender, signal location, signal color, and signal distance.

The traditional multinomial logit model (MNL) relates each individual outcome to a set of explanatory variables, but ignores correlated effects caused by variation within driver. In this study, there are on average, 87 data points (repeated measures) for each study participant. Hence, a mixed effects multinomial logit model (MMNL) is used to account for data with a group structure. That is, the random effects are included to appropriately account for the within group correlation (Harrel, Lee, Califf, Pryor, & Rosati, 1984). This model considers "drivers" and "tasks" as random effects using the Bayesian Markov Chain Monte Carlo (MCMC) method.

The relative utility associated with each pedal application type i for each driver d and each task t is represented with the general equation (Hensher & Greene, 2001):

$$U_{idt} = \beta_d X_{idt} + [\eta_{idt} + \varepsilon_{idt}] \qquad \text{(eq. 1)}$$

The parameter estimates are denoted by β_d, for independent variables, x_{idt}. The residuals are represented by η_{idt} and ε_{idt}, where η_{idt} is the residuals with zero mean whose distribution over individuals and alternatives depends on the underlying parameters and observed data related to task t, driver d and pedal application type, i and ε_{idt} is the residual of the random effect associated with each pedal application type, i, and is independently and identically distributed (i.i.d.) extreme value. Given the assumptions of the residuals, the conditional probability for the pedal application type, L_i, is defined simillarly to (McFadden & Train, 2000; Milton, Shankar, & Mannering, 2008) as:

$$L_{idt} = \frac{\exp\left(\beta_d x_{idt} + \eta_{idt}\right)}{\sum_j \exp\left(\beta_d x_{jdt} + \eta_{jdt}\right)} (\forall j \neq i) \quad \text{(eq. 2)}$$

The Bayesian methods based on MCMC simulation provides a more effective approach for model estimation when compared to traditional maximum likelihood estimation (MLE) (Burda, Harding, & Hausman, 2008; Mok, Sohn, & Ju, 2010). The multinomial logit model with repeated measures was performed in R (Version 2.15.2) with a Bayesian Markov Chain Monte Carlo using the MCMCglmm() package, with significance assessed at $\alpha < 0.05$. For the fixed effects priors, the variance-covariance matrix is set up to be exchangeable with the variance fixed at 1 for all of the diagonal terms and 0.5 for all of the off-diagonal terms (covariance) (Hadfield, 2009). When priors were not fixed, they are inverse-Wishart distributed. The burn in period equaled 30,000. The goal was to converge on a set of stable estimates for the model parameters. After the burn in period, we sampled each parameter from the model 60,000 times.

The other two dependent variables, pedal duration and pedal response time, were examined using linear mixed models with repeated measures, conducted with the “lme” function in the statistical package, R (ver 2.15.2). The independent variables, signal color, signal lane position and signal distance was considered in the model as well as the pedal application type. The pedal duration and response times were included for both pedal presses (brake and accelerator pedal). Pedal duration was log transformed to meet the normality assumption. The residuals for pedal response time were normally distributed and included in the model as collected.

3.3 Pedal Application Types

Each pedal application type was examined by the age groups (Table 4). The majority of applications were direct hits and each person had multiple direct hits (ranging from n=73 for those 75 and older, to n=83 for those 21 and younger). There were very few multiple occurrences for the other categories.

Table 4 Summary statistics for the four pedal application types

Pedal Application	Age Group	Count	Per Person Count	Percent
Direct Hits	< 21 yrs (n = 10)	825	82.50	25.26%
	26-55 yrs (n=14)	1054	75.29	32.27%
	60-74 yrs (n = 9)	658	73.11	20.15%
	>= 75 yrs (n = 10)	729	72.90	22.32%
Hesitations	< 21 yrs (n = 10)	19	1.90	12.67%
	26-55 yrs (n=14)	67	4.79	44.67%
	60-74 yrs (n = 9)	22	2.44	14.66%
	>= 75 yrs (n = 10)	42	4.20	28.00%
Corrected Trajectory	< 21 yrs (n = 10)	11	1.10	4.91%
	26-55 yrs (n=14)	69	4.93	30.80%
	60-74 yrs (n = 9)	87	9.67	38.84%
	>= 75 yrs (n = 10)	57	5.70	25.45%
Incorrect Pedal	< 21 yrs (n = 10)	18	1.80	14.64%
	26-55 yrs (n=14)	34	2.43	27.64%
	60-74 yrs (n = 9)	21	2.33	17.07%
	>= 75 yrs (n = 10)	50	5.00	40.65%

In the driving simulator study, a majority of pedal applications are correct responses. There were 123 pedal error responses (both pedals, miss, slip, incorrect trajectory) during the simulator study across all 43 participants; on average, 3 errors per person or about 1 error out of 31 foot movements were observed. It is interested to analyze both correct pedal responses as well as the pedal errors.

3.4 <u>Mixed Multinomial Logit Model: Predicting Pedal Application Types</u>

The multinomial logit model (Table 5) shows that when the stimuli were red, drivers were less likely to have a direct hit toward the correct pedal. More specifically, participants were 68.87 times more likely to respond with a corrected trajectory than a direct hit when there was a red signal. At a red signal, participants were 28.36 times more likely to be hesitant, and 3.48 times more likely to respond with a wrong pedal, slip, miss or touch both pedals than a direct hit.

Compared to the youngest group, all other age groups (i.e., middle-aged, older and oldest drivers) were more likely to respond with a corrected trajectory than a direct hit for both green and red signals. Under the same situation, the middle-aged and the oldest groups were more likely to be hesitated and the oldest drivers had the higher probabilities of responding with an incorrect pedal movement than a direct hit. Further examination of the older age group showed that those between 60 and 74 years old (n=9) had the highest number of corrected trajectories (total number = 87 out of 224) and those drivers older than 75 years old (n=10) had the most incorrect pedal movements (total number = 50 out of 123).

Subjects were 3.16 times more likely to change their foot trajectory rather than directly hit the pedal when the signal appeared closer. In the same situation, participants were 3.65 times more likely to have an incorrect pedal movement than a direct hit. When the stimuli were above the right lane to the drivers, they were more likely to have a direct hit rather than a corrected trajectory. Gender was omitted from the final model since it was not significant.

Table 5 Likelihood of a corrected trajectory, hesitation, or pedal error when compared to direct hit (baseline)

Corrected Trajectory vs. Direct Hit	Odd Ratio	Posterior Mean	95% CI	p value
Intercept		**-7.16**		
Signal: Red	**68.87**	**4.23**	**(3.21, 5.22)**	**< 0.0001**
Middle Age: 26-55 yrs old	**10.50**	**2.35**	**(1.29, 3.38)**	**< 0.0001**
Older Age: 60-74 yrs old	**28.27**	**3.34**	**(2.27, 4.50)**	**< 0.0001**
Oldest Age: >= 75 yrs old	**12.90**	**2.56**	**(1.38, 3.61)**	**< 0.0001**
Signal Distance: Closer	**3.16**	**1.15**	**(0.26, 2.10)**	**0.02**
Signal Lane: Right	**0.33**	**-1.12**	**(-2.09, -0.09)**	**0.02**
Hesitation vs. Direct Hit				
Intercept		**-5.91**		
Signal: Red	**28.36**	**3.35**	**(2.49, 4.16)**	**< 0.0001**
Middle Age: 26-55 yrs old	**5.01**	**1.61**	**(0.47, 2.62)**	**0.00**
Older Age: 60-74 yrs old	2.54	0.93	(-0.31, 2.05)	0.11
Oldest Age: >= 75 yrs old	**4.43**	**1.49**	**(0.29, 2.61)**	**0.01**
Signal Distance: Closer	*2.04*	*0.71*	*(-0.04, 1.47)*	*0.06*
Signal Lane: Right	**0.37**	**-0.99**	**(-1.91, -0.03)**	**0.03**
Pedal Error vs. Direct Hit				
Intercept		**-5.72**		
Signal: Red	**3.48**	**1.25**	**(0.29, 2.26)**	**0.02**
Middle Age: 26-55 yrs old	2.13	0.76	(-0.36, 1.91)	0.20
Older Age: 60-74 yrs old	2.00	0.69	(-0.50, 1.98)	0.25
Oldest Age: >= 75 yrs old	**4.33**	**1.47**	**(0.28, 2.60)**	**0.01**
Signal Distance: Closer	**3.65**	**1.30**	**(0.57, 2.03)**	**< 0.0001**
Signal Lane: Right	0.70	-0.36	(-1.19, 0.39)	0.37

Bold numbers indicate significance at $p < 0.05$
Italic numbers indicate significance at $0.05 < p < 0.1$

3.5 Repeated ANOVA: Pedal Duration and Response Time

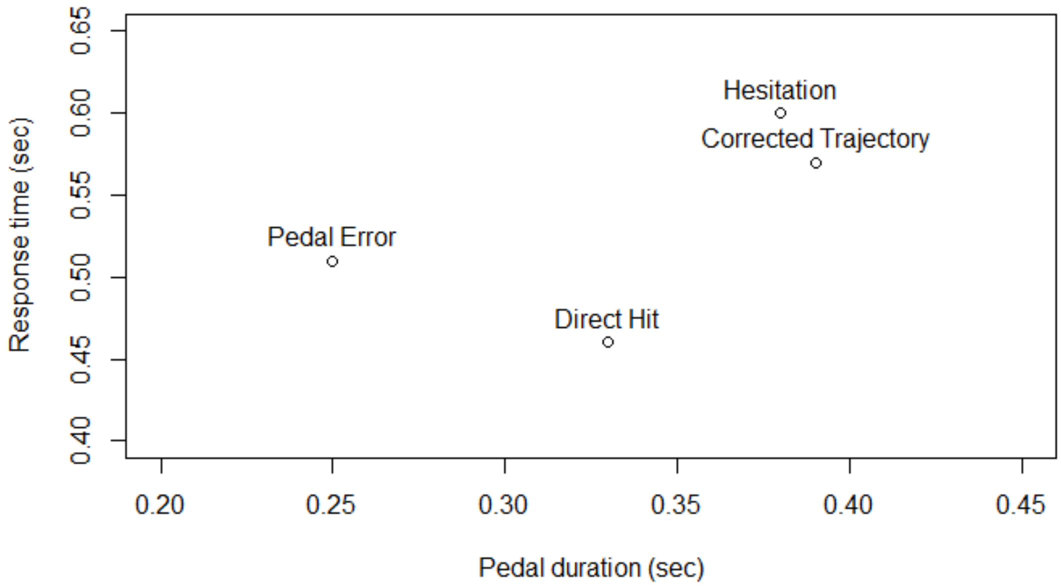

Figure 9 Comparison of mean pedal duration (in seconds) with mean response time (in seconds) for each pedal application

The mean and median reaction time was 0.47s and 0.46s, respectively, with values ranging from 0.05s to 1.26s. The mean and median pedal duration was 0.33s and 0.30s, respectively, with individual values ranging from 0.07s to 3.3s. Both the mean pedal duration and mean response time for direct hit and pedal error were shorter than that for corrected trajectory and hesitation (Figure 9).

Signals located further from the participant generated significant longer response time than signals closer to the participant ($F(1, 82) = 7.33$, $p<0.05$). Signal color also had an impact with longer response time for red signals when compared to green signals ($F(1, 290) = 5.63$, $p<0.05$). The interaction effect between signal color and pedal application ($F(3, 3566) = 4.8$, $p<0.05$) was significant, with longer response time observed for corrected trajectory and hesitation when the signals were red. Pedal application were significant ($F(3, 3570) = 72.16$, $p<0.0001$). Response time for direct hits was shorter than for the other three pedal applications.

The findings showed that signals located further from the participant generated marginally longer pedal durations than signals closer to the participant ($F(1, 84) = 3.58$, $p=0.06$). Signal color had an impact with longer pedal duration for red signals when compared to green signals ($F(1, 405) = 248.93$, $p<0.0001$). There was also a significant interaction effect between signal color and pedal applications ($F(3, 3622) = 9.19$, $p<0.0001$), with the shortest pedal duration observed for pedal errors with signals that were red. Pedal applications were significant ($F(3, 3608) = 61.50$, $p<0.0001$). Pedal duration time was longer for hesitations and shorter for pedal errors when compared to direct hit.

3.6 <u>Summary</u>

Using a driving simulator study, pedal application types were quantified based on foot trajectories. The pedal application types were predicted using a multinomial logit regression with repeated measures. Pedal duration time and reaction time were then examined for various drivers' characteristics and in different traffic signal conditions. This chapter revealed the impact of various drivers' characteristics and situational factors. However, there may be other driver-related differences associated with the foot reach toward the brake pedal and this is further explored in the next chapter.

CHAPTER 4. FUNCTIONAL DATA ANALYSIS ON FOOT TRAJECTORIES

Chapter 3 described the different categories of pedal applications and foot behavior from the driving simulator study. It is of interest to further analyze drivers' foot behavior while approaching the brake pedal. This will address research question 2: What variations exist in drivers' foot-to-pedal behavior? In order to analyze drivers' foot movements towards the pedal, a motion detection technique is used to extract foot trajectories from the video data collected in the driving simulator study. Functional data analysis is then applied to visualize the components associated with the variations. The most common patterns associated with drivers pressing the pedal(s) will be summarized based on the dominant modes of variation from multiple pedal application trajectories.

4.1 Method: Functional Data Analysis

4.1.1 Data

The dataset used in this study came from the experiment using an instrumented vehicle secured in a stationary position of the driving simulator environment. Motion detection technique was engaged to extract drivers' foot trajectories for every brake pedal application. A foot movement example was shown in Figure 10, as the driver's foot started from the floor and moved to reach the brake pedal. In order to analyze the entire procedure of a pedal application, the side view (Figure 10 a) was used for motion detection.

Foot trajectories were detected and recorded for every brake pedal application for 45 drivers (21 females and 24 males). Each driver had 9 brake pedal applications during the experiment. The foot trajectories were traced 30 times per second and were recorded in

X, Y coordinates (in unit of pixels) matched using time stamps. Excluding missing data and low video qualities, 346 pedal applications were used in the analysis.

(a) (b)

Figure 10 An example of pedal application foot trajectory

4.1.2 Functional Data Analysis

The overall goal of the analysis is to capture a profile of different pedal behavior. To do this, a spline is initially fit as a basis function for each task completed by the driver. Functional PCA is then applied to the splined curves to identify a reduced set of components with the primary modes of variation in the data, or alternatively to provide the greatest insights into the changes in pedal movement. The components observed in the functional PCA for the direct hit and corrected trajectories are then compared to the trajectories observed in the pedal errors. Those that are not similar to the direct hits and corrected trajectories are then investigated further.

Functional Principal Component Analysis

By nature of foot movement, the foot to pedal trajectory is a continuous function over time. Using motion detection technique on the video, the foot trajectory data was represented in X and Y coordinates for every 1/30 second (i.e., discrete observations). Thus functional representations can be used to reconstruct every continuous foot movement curve (Ramsay & Silverman, 2006). Choosing an appropriate function basis can capture the shape of sampled data and also possess convenient computational properties (Ramsay & Silverman, 2002). B-Splines, which are made of polynomials each one spanning a limited interval and then compose together smoothly, were used in this study. The B-spline functions were fitted by minimizing the sum of squared errors (Graves, Hooker, & Ramsay, 2009). The order of four was selected for the B-splines (i.e., cubic B-spline), and 26 numbers of knots were chosen for drivers' foot position. The cubic B-spline function with k knots has the basis expansion:

$$f(x) = \sum_{j=1}^{K+4} B_j^4(x)\beta_j \qquad \text{(eq. 3)}$$

where $B_j^4(x)$ is the set of cubic B-splines basis functions.

Different patterns in foot movement were observed among different drivers or even within the same driver. Principal components analysis (PCA) provides a way to extract and display the main modes of variation of a set of multidimensional data (Graves et al., 2009). That is, PCA can be used to summarize the variations with little loss of original information and explain whether variations in foot trajectories were dominated by certain major patterns. Instead of using the weight vector in the traditional PCA, the motivation is to define a 2-vector weight function $\xi = (\xi^x, \xi^y)'$ (Graves et al., 2009; Ramsay & Silverman, 2006), with ξ^x refers to the variation of foot movement curve in the x coordinate and ξ^y that in the y coordinate. Thus, the weighted linear combination becomes:

$$f_i = \int \xi^x x_i + \int \xi^y y_i \qquad \text{(eq. 4)}$$

Based on the eigen-equaion system $V\xi = u\xi$, the solution could be extracted:

$$\int v_{xx}(s,t)\,\xi^x(t)dt + \int v_{xy}(s,t)\,\xi^y(t)dt = u\xi^x(s) \qquad \text{(eq. 5)}$$

$$\int v_{yx}(s,t)\,\xi^x(t)dt + \int v_{yy}(s,t)\,\xi^y(t)dt = u\xi^y(s) \qquad \text{(eq. 6)}$$

where, v_{xx} is defined as the covariance operator of the foot movements in x coordinate and v_{yy} that of the y coordinate; v_{xy} is the cross-covariance function, and $v_{xy}(s,t) = v_{yx}(s,t)$. The eigenvalues of the variance-covariance function are indicators of the importance of the principal components.

Functional k Nearest Neighbors Algorithm

A simple k nearest neighbors cluster analysis was applied on the functional data. The number of k nearest neighbors was chosen based on the minimum generalized cross validation estimate. All the analysis was conducted in the statistical package R (version 2.15.2).

4.2 Functional Principal Component Analysis on Foot Trajectory

4.2.1 Foot trajectory curves

Figure 11 showed the mean foot trajectory curve for direct hit pedal application (green), corrected trajectory (orange) and pedal error (red), as the driver's foot started from the bottom right corner and targeted to the brake pedal on the upper left corner. Direct hit means the driver directly hit the correct pedal; while corrected trajectory refers to the situation when the driver corrected the foot movements before reaching the correct pedal. On average, corrected trajectory had higher trajectory than direct hit. Several types of pedal errors were observed during the experiment: miss the pedal, slip from the pedal, press the gas pedal and press both pedals. All these pedal applications were considered as pedal error. Pedal error show lower ending points than the other two categories on average and pedal errors also encompass more variations.

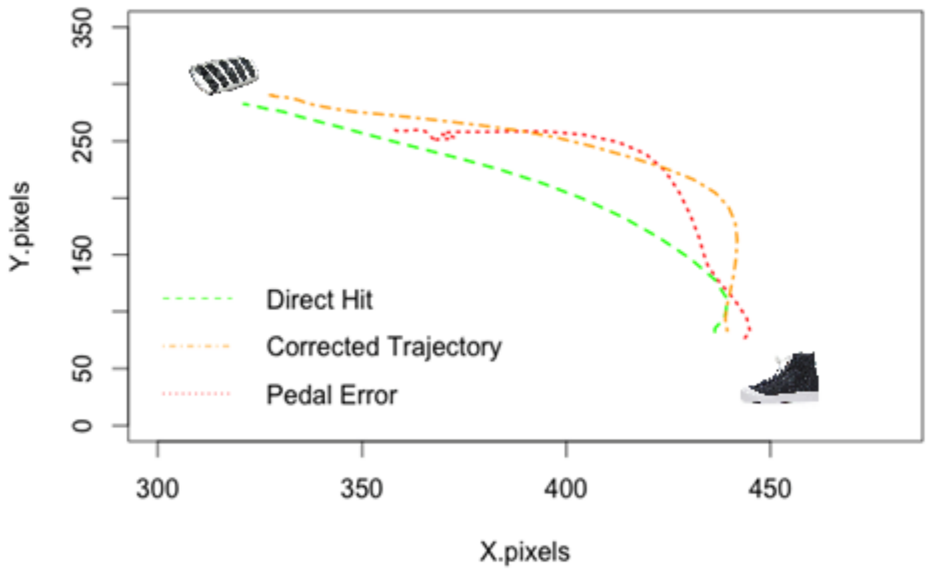

Figure 11 Plot of mean curves for Direct Hit (green), Corrected Trajectory (orange) and Pedal Error (red)

Each foot trajectory curve in Figure 12 represented a complete brake pedal application process. The green curves referred to direct hits, orange for corrected trajectories and the red lines represented pedal errors. The dominant pattern of foot trajectories is cruciform-shaped with large fluctuations. Compared to the direct hits, the corrected trajectories had more variations as indicated by the red circle in the figure. Pedal errors also involved more variations with some random patterns, which included very high, very low foot trajectories and changing behaviors.

4.2.2 Functional Principal Component Analysis

Different patterns of foot movements were observed during this study. The question of interest is how drivers move their foot to the brake pedal and where the variations would be located. Analyses are segmented according to the pedal response types (i.e., direct hit, corrected trajectory and pedal error). The knots (time) were specified and 26 cubic B-spline basis functions with order of four were defined. This placed a knot at every other observation points. This was found to correspond closely to spline smoothing result.

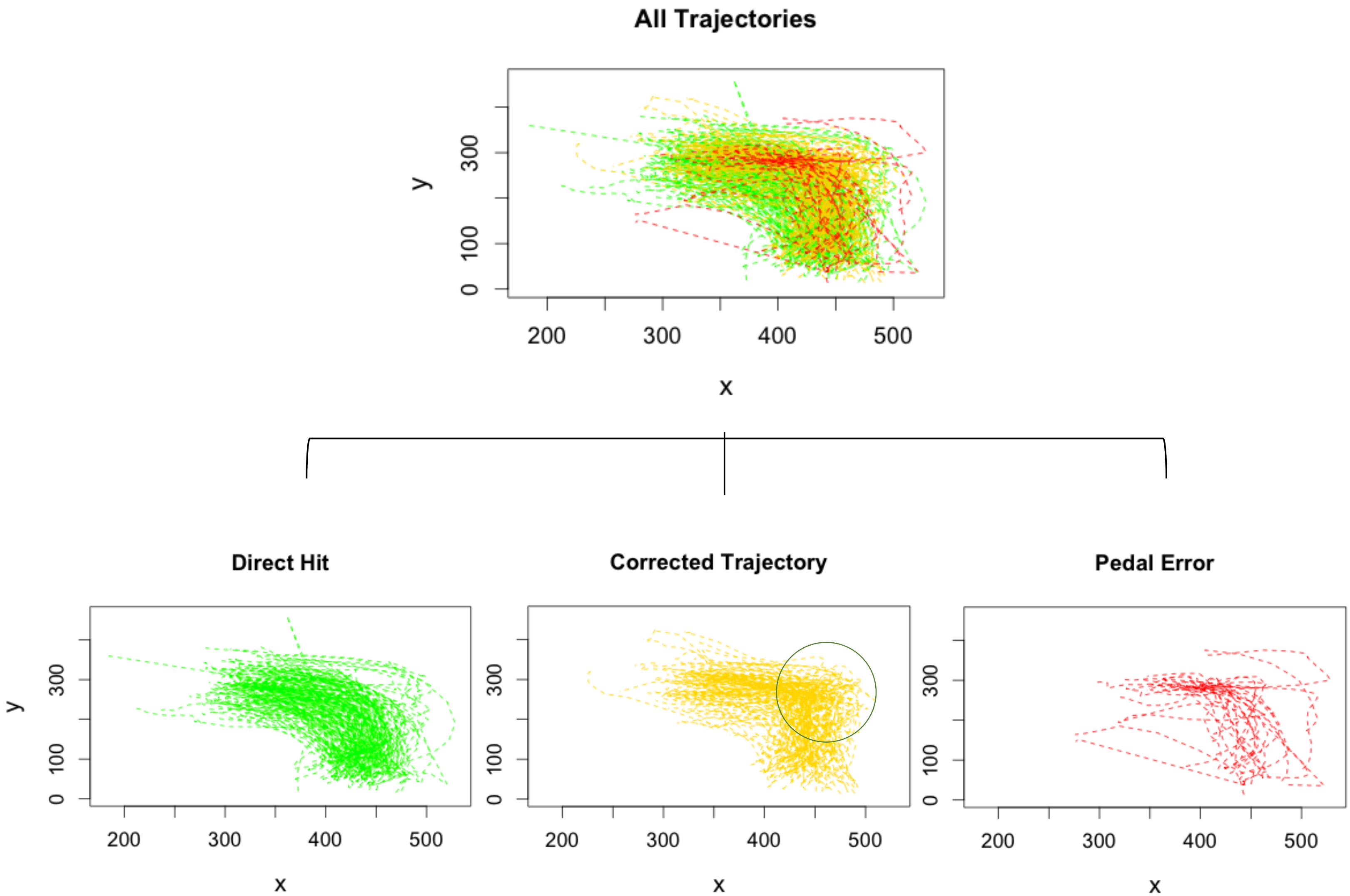

Figure 12 Plots for pedal application trajectories ([top] all pedal application trajectories; [bottom left] green dashed line: Direct Hit; [bottom middle] orange line: Corrected Trajectory; [bottom right] red line: Pedal Error;)

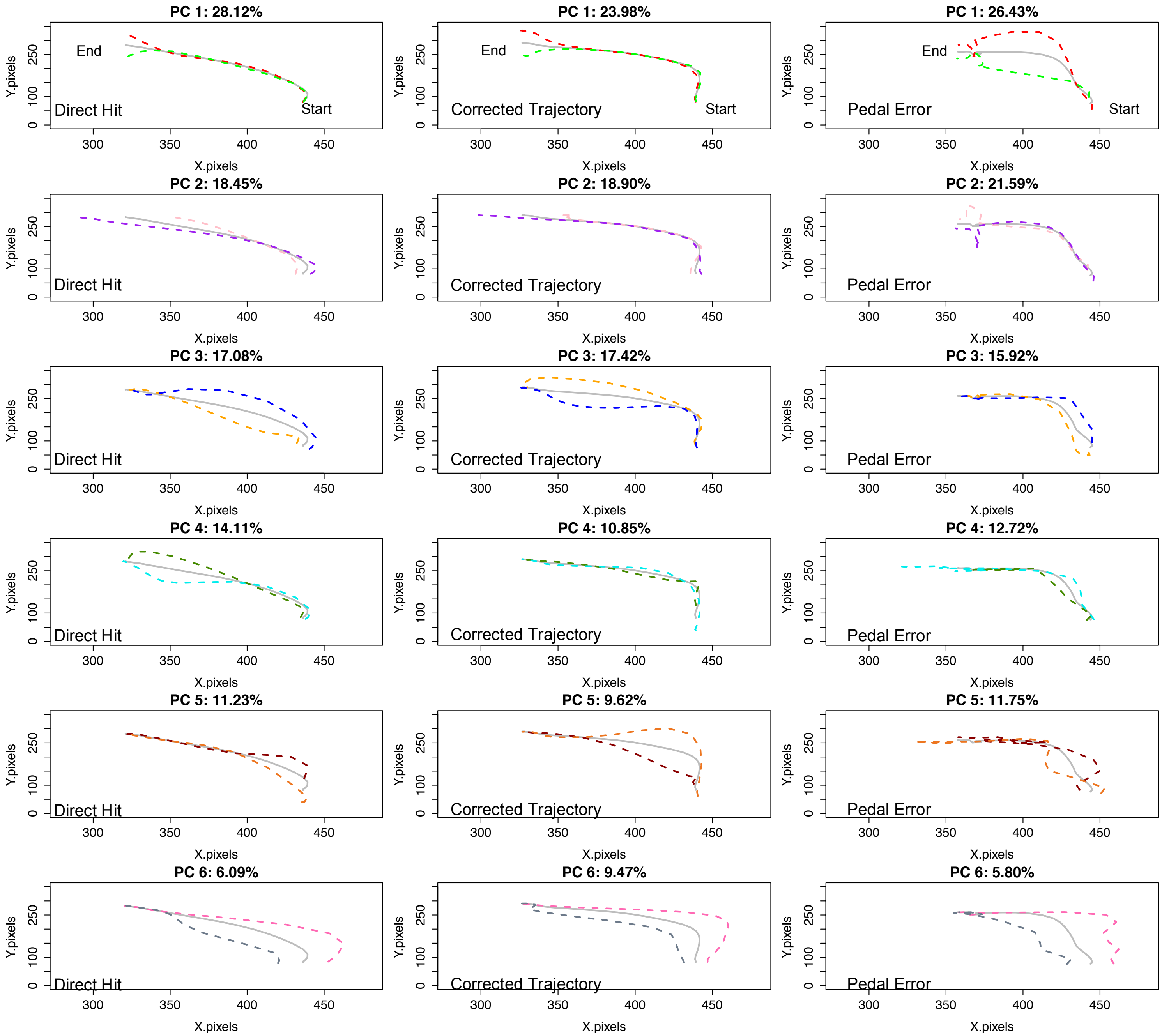

Figure 13 Plots of the first three VARIMAX-rotated eigen-functions as perturbations of the mean script

A useful way to visualize the variation is to plot curves corresponding to the mean foot trajectory (solid line) alongside the upper and lower bounds for each principal component. In classical multivariate analysis, an appropriate rotation of the principal components can generate a more informative indicator than the original components themselves. Similarly, a VARIMAX rotation was used here to maintain orthogonality when rotating the principal components. The first six of the VARIMAX-rotated eigenfunctions area are shown in Figure 13, and account for over 90% of the variation associated with the three different types of pedal responses: direct hit (left column, 95.08% of the variation), corrected trajectory (middle column, 90.23%) and pedal error (right column, 94.20%).

The majority of variability can be explained in the first three components (63.65%, 60.3%, and 63.94% for the direct hit, correct trajectory, and pedal errors, respectively). For direct hit, the majority of variation can be explained by the position of the foot at the end of the trajectory, when the driver is about to touch the pedal (shown in components 1 and 2: 28.12%, 18.45%, respectively), this is followed by the other part of the foot movement (component 3). This is similar to the movements associated with correct trajectories, which is also associated with the end movements (component 1: 23.98% and component 2: 18.90%). However, for pedal errors, the largest contribution is from the middle portion and the end movement of the trajectory (component 1: 26.43%, component 2: 21.59%), followed by the variation at the beginning (component 3). In other words, pedal errors have very different characteristics and the differences in movements are more prominent in the middle portion of the trajectory. The pedal error category showed that the change in foot trajectories (amplitude) for the first component varied greatly (274.49 pixels) among drivers when compared to the first component of direct hit (242.57 pixels) and corrected trajectory (252.17 pixels).

Taking the six PC's into account, there were similar patterns between the corrected trajectory and the direct hit. The variations within these pedal types could be separated into five parts. The first two parts contained the majority of the variability and were associated with the vertical and horizontal variations in foot movements when the foot was about to touch the pedal. The third part was the middle part, as the foot was already lifted from the floor and on the way to the pedal. Then, there were variations in the procedure as the driver raising the foot from the floor. The last part captured any other types of variation during the entire pedal application process.

The PC 3 of direct hit (17.08%) and the PC 4 of corrected trajectory (10.85%) were unique among all other categories. The curves in the corrected trajectory PC 4 (especially the dark green dotted line) showed the pattern of foot trajectories changing. The foot trajectories were more unpredictable for pedal errors, as can be seen from the first, second and fifth PC, specifically. The curves showed unusual foot movement patterns and covered some areas that were not covered by the other two categories.

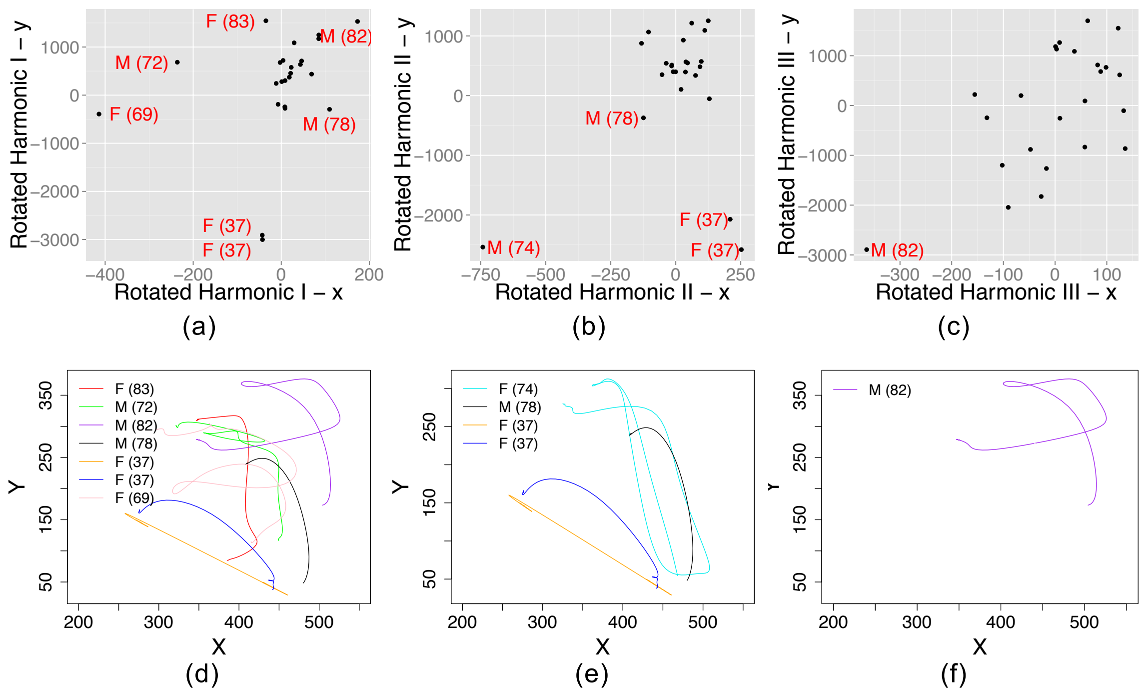

Figure 14 Trajectory of pedal errors with the scores for VARIMAX-rotated principal components I, II and III, with labels [gender (age)] for outliers (top row), and the functional foot trajectories of outliers (bottom row).

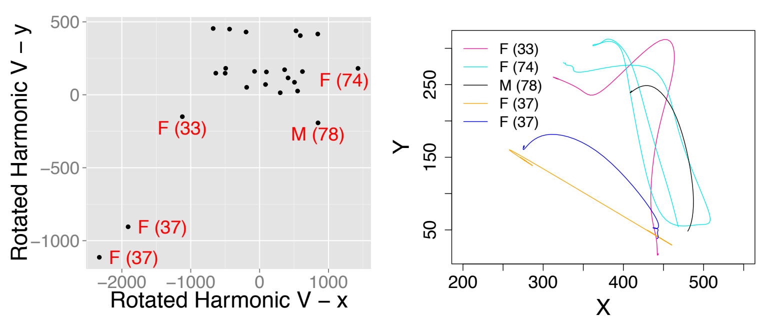

Figure 15 Trajectory of pedal errors with the scores for VARIMAX-rotated principal components V, with labels [gender (age)] for outliers (left), and the functional foot trajectories of outliers (right).

A further segmentation of components 1, 2 and 3 for the pedal errors were conducted. The distribution of the principal component scores and foot trajectories for selected pedal applications are shown in Figure 14, and to distinguish the pedal errors from non pedal errors, Figure 15 shows the additional unique harmonic (PC 5) from the six-dimensional subspace (as identified by the eigen-functions). Each dot in the figure represented one pedal misapplication for a driver. Most of the dots were clustered as a group. Some dots were separated from the majority as they had very high absolute values in either the x or y coordinate, or both. They could be potentially outliers as those drivers might exhibit different behavior and were identified in terms of gender and age shown in red labels.

The 82 year-old male driver appeared in both PC 1 and PC 3 scores plots, who had extremely different movement patterns in both x and y coordinates (Figure 14 d and 14 f). A 72 year-old male driver and a 69 year-old female driver had huge variations in the x coordinate and the green and pink curve in Figure 14 d demonstrated this finding. A 37 year-old female driver had her foot slipped from the pedal twice (the orange and blue curves in Figure 14 d and 14 e) when responding to red signals, hence her foot trajectory had relatively low height and large absolute PC scores.

As an exploratory study, a functional k nearest neighbor was developed for the foot trajectories of direct hit and corrected trajectory. The pedal error category contained much fewer observations but encompassed many different trajectories. Hence, the k nearest neighbor would have pulled the pedal errors toward a grouping associated with the direct hit and/or corrected trajectory, which is not our intent. The original data were randomly separated into a training set, which contained 75% of the original data, and a test set with 25% of the data. The parameter k = 3 (# of nearest neighbors) was selected when the model achieved the minimum generalized cross validation estimate. The training model had an accuracy of 78.49% in predicting pedal response categories and the accuracy for the test dataset was 72.86%.

4.3 Summary

Drivers' brake pedal applications were observed from the video data captured in the driving simulator study. Motion detection technique was applied to extract foot trajectories from the videos. Foot trajectories were grouped into three pedal response categories (i.e., direct hit, corrected trajectory and pedal error) based on the foot trajectory and the outcome of the pedal application. Functional principal component analysis was then applied to the foot trajectories, which revealed the common patterns and identified the components that contribute the most to the variability in the observed pedal applications. In the next chapter, similar pedal response categories are summarized from a naturalistic driving study. Independent variables, including drivers' characteristics and real world driving scenarios that associate with pedal response and foot placements are explored.

CHAPTER 5. FOOT BEHAVIOR IN NATURALISTIC DRIVING STUDY

Chapters 3 and 4 showed the results of the driving simulator study. This chapter covers the data analysis and results from the naturalistic driving study (described earlier in Chapter 2). Within a four-week study, 680 events that contained a pedal error or potential pedal error were captured. The research question 3 is addressed in this chapter: Does foot behavior differ in terms of context and driver characteristics? For the purpose of comparing the results from the simulator driving and the naturalistic driving study, drivers' pedal application types are grouped into similar categories as described in Chapter 3. It is of interest to study how drivers place foot prior and during the event and whether there is a relationship between foot placement and the pedal application types. Classification models are applied on drivers' pedal application types and foot placements in terms of different context and drivers' characteristics.

5.1 List of Variables

5.1.1 Explanatory Variables

Data collected from the drivers included demographic variables (age, gender), driving history (miles driven per year), and daily driving behavior. Anthropometric dimensions were collected during the experiment, including height, weight, foot length and width. Number of errors, number of restarts in the trail making cognitive test and time to finish the trails were considered as the assessment of participants' cognitive functions and were included in the analysis. The drivers' daily exercise levels were also collected from the pre-trip questionnaire.

Each trip in the naturalistic driving study was coded for trip type, sequence type (start-up sequence, parking sequence and driving sequence), shoe characteristics (shoe type, heel type, back type and shoe toe coverage), start date/time, total run time, and notable foot movement behaviors before and during events. Driving behaviors, such as turning, heel touch the floor and back away from the chair were also coded from the video.

Foot placements prior to the events were identified into three categories: (i) on brake (n = 437) (baseline), (ii) on accelerator (n = 199), and (iii) not on the pedal (n = 44). The "not on pedal" category contained several types of foot placements, including hesitation (n = 1), on the floor (n = 11), transition to pedal (n = 2), hover over the brake pedal (n = 6) and hover over the accelerator pedal (n = 24). Each sub-category of the pedal error had a few observations hence they were combined.

5.1.2 Response Variables

Pedal response types

There were numerous pedal applications observed during the four-week study period. For this study, only notable foot movements and incorrect pedal applications were categorized (Table 6). Pedal applications were classified based on video analyses of the trajectory of foot movements. The categories were similar to the pedal response types in Wu et al (2015), but were modified according to the real world driving situations. The foot movements were grouped into two main categories: (i) notable foot movement (n = 565) and (ii) pedal error (n = 57). Notable foot movements refer to either correct or incorrect pedal applications that have the potential to result in pedal errors. In total, there were three classifications of notable foot movement and four classifications of incorrect pedal placement (or pedal errors) identified. The most frequent pedal responses observed were the incorrect trajectory (n = 284, 50.27%), followed by uncertainty (n = 168, 29.73%) and back pedal hook (n = 113, 20%).

Table 6 Classification of pedal errors in ND study

	Category	n	Definition
Pedal Error	**Wrong pedal**	13	Driver hit incorrect pedal.
	Miss	33	Driver attempted to hit a pedal, but missed it entirely.
	Both pedals pressed	7	Driver pressed both pedals at the same time.
	Pedal slip	4	Driver's foot slipped off pedal and puts it back on correct pedal.
Notable foot movement	**Incorrect trajectory**	284	Driver hit wrong pedal on the way to hitting the correct pedal.
	Uncertainty	168	Driver wagged foot laterally or in z-direction at least 2 times in 2 directions; unsure of which pedal to hit.
	Back pedal hook	113	Driver hit underside or side of brake pedal when lifting foot off gas pedal.

Foot placement

Drivers' foot placements prior and during the notable movements (events) were coded from the video data. Foot placements during the events was used as the dependent variables in the statistical model with three categories: (i) on brake (n = 307) (baseline), (ii) in transition (n = 166), and (iii) pedal errors (n = 206). The pedal error category contained several types of errors, including press both pedals (n = 8), hesitation (n = 175), on the floor (n = 10), on accelerator pedal (n = 10) and hover over the accelerator pedal (n = 3). Each sub-category of the pedal error had very few observations and where therefore combined into one category.

5.2 Data Analysis

5.2.1 Random Forest

Random forest is a learning method for classification or regression, which consists of a number of decision trees. The data is initially separated into a training set and a testing set. This algorithm developed from the training set outputs the final class label as the mode of the individual predicted classes.

In this current study, 500 decision trees were grown based on two thirds of the training data. At each node, a subset of variables was considered at each split. In this current study, about $\sqrt{k}$ features, where k is the total number of features (k = 32), were randomly selected for each partition. The 32 features came from surveys, video, and anthropometric tests (Table 12). For each tree, the remaining one-third data were used as the validation dataset to compute the out-of-bag (OOB) error rate. All the decision trees voted for the finalized output class label. Random forest accounts for over-fitting, which is a common problem with a single decision tree. The entire procedure of random forests was shown in Figure 16 and was performed in R (Version 2.15.2).

The random forest algorithm calculated the Gini importance of each variable in this classification problem. The Gini importance indicates the frequency a feature was selected for a split and its overall discriminative value to the classification problem. The importance could be interpreted as the comparison statistic between variables in the model (Menze et al., 2009). A higher mean decrease in Gini refers a particular variable is more important in partitioning the data into classes.

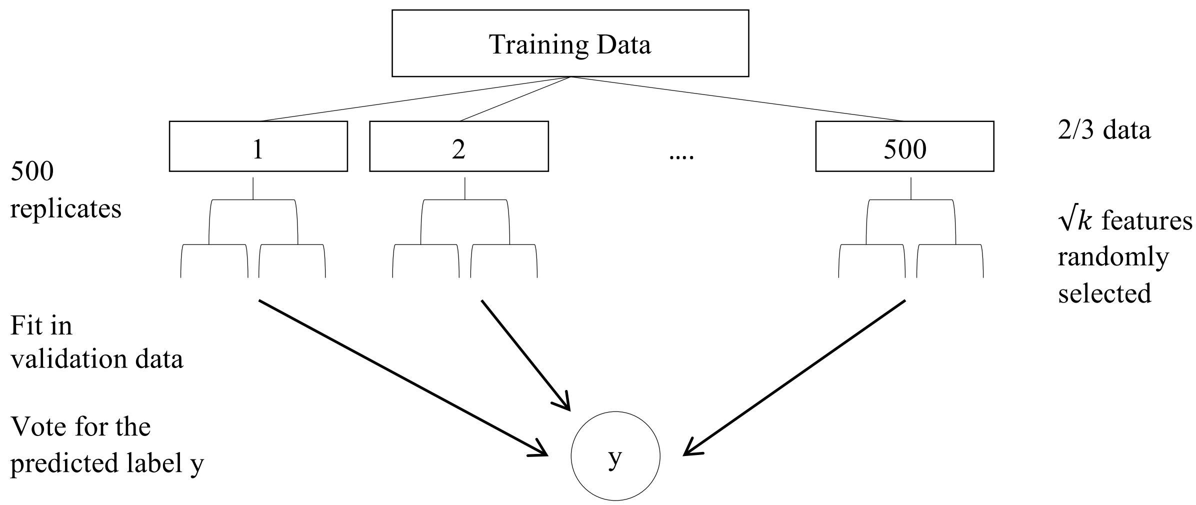

Figure 16 Random forest algorithm

5.2.2 Multinomial Logit Regression with Repeated Measures

A mixed effects multinomial logit model (MMNL) was used to predict the likelihood of a foot placement being in one of four categories: back pedal hook, incorrect trajectory, uncertainty and pedal errors. The explanatory variables (or independent factors) included in the model were drivers' characteristics, driving histories and driver behavior in the trip.

The traditional multinomial logit model (MNL) relates each individual outcome to a set of explanatory variables, but ignores correlated effects caused by variation within driver. In this study, there were 668 foot movements observed for the 30 participants (i.e., on average, 22 notable foot movements or pedal errors (repeated measures) for each driver). The repeated measures were included in a mixed effects multinomial logit model (MMNL) to appropriately account for the within group correlation (Harrel et al., 1984). This model considered "drivers" as random effects using the Bayesian Markov Chain Monte Carlo (MCMC) method.

The relative utility associated with each foot placement i for each driver d was represented with the general equation (Hensher & Greene, 2001):

$$U_{id} = \beta_d X_{id} + [\eta_{id} + \varepsilon_{id}] \quad \text{(eq. 7)}$$

The parameter estimates are denoted by β_d, for independent variables, X_{id}. The residuals were represented by η_{id} and ε_{id} , where η_{id} was the residuals with zero mean whose distribution over individuals and alternatives depends on the underlying parameters and observed data related to driver *d* and foot placement type, *i* and ε_{id} was the residual of the random effect associated with each pedal application type, *i*, and was independently and identically distributed (i.i.d.) extreme value. Given the assumptions of the residuals, the conditional probability for the foot placement category, L_i, could be expressed simillarly to (McFadden & Train, 2000; Milton et al., 2008) as:

$$L_{id} = \frac{\exp\left(\beta_d x_{id} + \eta_{id}\right)}{\sum_j \exp\left(\beta_d x_{jd} + \eta_{jd}\right)} (\forall j \neq i) \quad \text{(eq. 8)}$$

The Bayesian methods based on MCMC simulation provided a more effective approach for model estimation when compared to traditional maximum likelihood estimation (MLE) (Burda et al., 2008; Mok et al., 2010). The multinomial logit model with repeated measures was performed in R (Version 2.15.2) with a Bayesian Markov Chain Monte Carlo using the MCMCglmm package, with significance assessed at $\alpha < 0.05$. For the fixed effects priors, the variance-covariance matrix was set up to be exchangeable with the variance fixed at 1 for all of the diagonal terms and 0.5 for all of the off-diagonal terms (covariance) (Hadfield, 2009). When priors were not fixed, they were inverse-Wishart distributed. The burn in period equaled 20,000. The goal was to converge on a set of stable estimates for the model parameters. After the burn in period, we sampled each parameter from the model 50,000 times.

5.3 Descriptive Analysis

Thirty participants (16 females and 14 males) with mean age 29 years old (sd = 4.79, median = 30) for the younger group (18-35 years old) and mean age of 70 years old (sd=4.6, median = 68.5) for the older group (≥ 65 years old) were included in the Naturalistic Driving (ND) study. In total 3385 trips were collected and over 2700 of the trips did not involve an error. Only the trips that contained at least one notable foot movement or pedal error will be included in the following data analysis. Table 7 showed the counts for different types of movements/pedal errors during varying driving tasks. Among all the foot movements, only 59 (8.7%) were pedal errors and 585 (86.0%) were notable foot movements. Table 8 presented foot positions on the brake prior to, during, and after a potential error. Most of foot placements were on the upper portion and covered the right 2/3 of the brake prior (46.3%, n = 203) and after (45.2%, n = 112) a potential error. However, during a potential error, a majority of the foot placements (85.9%, n = 268) were on the lower portion and only covered the right 1/3 of the brake.

Table 7 Pedal misapplication classification

Type of potential errors		Sequence type			
		Normal driving	**Parking Sequence**	**Start-up Sequence**	**Total**
Notable foot movement errors	Back Pedal Hook	48	22	43	113
	Incorrect trajectory	119	43	125	287
	Uncertainty	62	45	66	173
	Reposition of foot on pedal	4	3	5	12
Pedal errors	Wrong pedal pressed	2	4	8	14
	Both pedals pressed	6	0	1	7
	Miss	4	2	27	33
	Pedal slip	3	1	1	5
Other errors	Other	11	6	19	36

Table 8 Foot positions on brake prior to, during, and after a potential error

Prior to a potential error	Lower portion	Upper portion	Total
Covers all of brake	8	120	128
Left 2/3	1	19	20
Right 2/3	24	203	227
Right 1/3	40	23	63
During a potential error	**Lower portion**	**Upper portion**	**Total**
Covers all of brake	0	3	3
Left 2/3	0	0	0
Right 2/3	1	4	5
Right 1/3	268	36	304
After a potential error	**Lower portion**	**Upper portion**	**Total**
Covers all of brake	3	58	61
Left 2/3	1	9	10
Right 2/3	13	112	125
Right 1/3	24	28	52

As observed in Table 8, a relationship between the vertical and horizontal foot positions with respect to the brake pedal can be observed. The results for foot placements on the accelerator pedal are presented in Table 9. There were less accelerator pedal applications during the potential errors since most drivers moved their foot to the brake pedal during the event. Drivers usually moved their foot back to press the accelerator pedal after the error.

Table 9 Foot positions on the accelerator

	Prior to potential error	During	After	Total
Lower portion	54	9	99	162
Middle portion	80	3	183	266
Upper portion	68	5	133	206
Total	202	17	415	634

Different types of shoes were associated with the different pedal application types (Table 10). Because some categories contained very few observations (e.g., Crocs and slippers), no significant differences were observed, and all footwear categories were combined for the statistical model(s). It is interesting to note that only two events were associated with slippers, and both of these events were categorized as the wrong pedal.

Table 10 Types of shoes observed vs. pedal application types in ND study

	Incorrect trajectory	Uncertainty	Back Pedal hook	Wrong pedal	Miss	Slip	Both pedals	Total
Athletic shoes	131	76	53	5	13	4	3	285
Boots	37	25	30	2	1	0	2	97
Causal/loafers/ Dress	57	48	21	2	10	0	0	138
Crocs	1	1	0	0	0	0	0	2
No shoes/bare feet or socks	0	2	0	0	1	0	0	3
Sandals	58	16	0	2	8	0	2	86
Slippers	0	0	0	2	0	0	0	2
Total	284	168	104	13	33	4	7	613

5.4 Predicting Pedal Responses

A Random Forest algorithm was applied to all 32 variables (Table 12). The data set was randomly separated into training (80%) and testing (20%) data. The out-of-bag (OOB) estimate of training error rate was 8.60%. The confusion matrix for each pedal application type was shown in Table 11. The test error rate was 6.56% with the confusion matrix shown in Table 13.

Table 11 Confusion matrix for pedal application types prediction (training)

	Back Pedal Hook	Incorrect trajectory	Uncertainty	Pedal Error	Training error
Back Pedal Hook	83	2	0	3	0.06
Incorrect trajectory	2	229	2	0	0.02
Uncertainty	0	0	126	8	0.06
Pedal Error	1	7	18	19	0.58

Table 12 showed the list of all variables and their importance in descending Gini order. A higher Gini statistic shows the importance of a particular variable/feature in partitioning the data into classes. The variable with the highest mean decrease Gini was driver's right foot placement during the error, while the second most important variable is the driver's foot placement prior the error. Other variables are associated with the drivers' cognitive functions such as the time spent in trail A and B and number of errors in trail B. The anthropometric measurements (i.e., foot length, weight, standing height and foot width) also played an important role in the prediction. Furthermore, whether the vehicle was turning was an important situational variable.

Table 12 List of variables and the mean decrease in Gini

Category	Variable	Mean Dec Gini
Video/Foot	Right foot placement during error	142.34
Video/Foot	Right foot placement prior to error	49.62
Cognitive	Trail A time	8.35
Anthropometric	Weight	7.34
Anthropometric	Foot Length	7.29
Video/Foot	Turn	6.88
Anthropometric	Standing Height	6.57
Cognitive	# of errors in trail B	6.51
Cognitive	Trail B time	6.05
Anthropometric	Foot Width	5.83
Driver	Miles driven per year	5.54
Video/Foot	Shoe types	5.25
Video/Foot	Environment	4.51
Video/Foot	Glance prior to error	4.11
Cognitive	# of errors in trail A	4.07
Video/Foot	Back away from chair	3.70
Video/Foot	Glance during error	3.64
Video/Foot	Light condition	3.41
Video/Foot	Distractor	3.24
Video/Foot	Shoe ties	3.23
Video/Foot	Shoe heel type	3.15
Video/Foot	Heel touching floor	3.06
Video/Foot	Shoe back type	2.86
Driver	Exercise regularly	2.82
Video/Foot	Road surface	2.31
Cognitive	# of restarts in trail B	2.22

Video/Foot	Torso turn	2.01
Video/Foot	Shoe toe coverage type	1.47
Video/Foot	Weather	1.12
Driver	Gender	1.06
Driver	Age Group	0.97
Cognitive	# of restarts in trail A	0.50

Table 13 Confusion matrix for pedal application types prediction (testing)

	Back Pedal Hook	Incorrect trajectory	Uncertainty	Pedal Error	Test error
Back Pedal Hook	24	0	1	0	0.04
Incorrect trajectory	0	51	0	0	0.00
Uncertainty	0	0	34	0	0.00
Pedal Error	1	5	1	5	0.58

This algorithm could be applied in a driver assistance system to assist the driver in pedal applications under various situations. In this naturalistic study, several notable foot movements were observed and some of them were considered as errors and some could potentially lead to errors. But all drivers were able to recover from the errors and hence, no incidents occurred. In practice, a model that could predict the pedal application types as early as possible would be useful to provide the assistive system sufficient time to generate an alert and help assist drivers in correcting potential errors. The variable "foot placement during error" had the highest importance index (Gini), and the error rate increased to 31.2% if this variable has been taken out from the model. There was a relationship between foot placement during error and the pedal response types, as shown from the random forest algorithm. However, foot placement during error could be associated with foot placement prior to error; and the association could be applied to improve the predicting algorithm.

5.5 Foot Placement on the Pedals

A multinomial logit model with repeated measures was applied to predict drivers' foot placement during the event (Table 14). The dependent variable had three levels: made an error, foot in transition and foot on the brake pedal (baseline). If the driver's foot was on the accelerator pedal before the error, then the driver's foot was 10.34 times more likely to make an error when compared to foot on the brake pedal before the error. The same situation was more likely to lead to foot being in transition but this variable was marginal significant ($p = 0.10$). If the driver's foot was on the brake pedal before the event, the driver was less likely to make an error or had foot being in transition (odd ratio = 0.24 and 0.01, respectively) compared to pressing the brake pedal.

Table 14 Estimates of the right foot placement during an error (when compared to on the brake)

Compare to "on the brake" (baseline)		Posterior mean	95% CI	p value	
(Intercept)	Error	1.67	(-1.04, 4.49)	0.22	
(Intercept)	Transition	-0.36	(-3.24, 2.29)	0.79	
Right foot placement prior: Accelerator	Error	2.34	(0.93, 3.90)	0.00	**
Right foot placement prior: Accelerator	Transition	1.13	(-0.16, 2.63)	0.10	
Right foot placement prior: Brake	Error	-1.44	(-2.70, -0.02)	0.03	*
Right foot placement prior: Brake	Transition	-4.84	(-6.06, -3.58)	0.00	***
Age group: Young	Error	0.20	(-1.15, 1.35)	0.73	
Age group: Young	Transition	1.38	(0.22, 2.65)	0.02	*
Sequence type: Parking sequence	Error	0.84	(0.08, 1.58)	0.03	*
Sequence type: Parking sequence	Transition	1.21	(0.27, 2.24)	0.02	*
Sequence type: Start-up sequence	Error	0.26	(-0.35, 0.89)	0.43	
Sequence type: Start-up sequence	Transition	1.21	(0.39, 1.95)	0.00	**
Heel touching floor	Error	-0.51	(-1.29, 0.30)	0.22	
Heel touching floor	Transition	-1.48	(-2.36, -0.63)	0.00	**
Back away from chair	Error	0.13	(-0.66, 0.92)	0.74	
Back away from chair	Transition	-0.91	(-1.84, 0.05)	0.06	.
Exercise	Error	1.09	(-0.05, 2.27)	0.07	.
Exercise	Transition	0.31	(-0.75, 1.35)	0.55	
Miles driven per year	Error	-0.49	(-1.07, 0.17)	0.10	
Miles driven per year	Transition	0.57	(-0.03, 1.16)	0.06	.
Turn left	Error	-0.20	(-0.86, 0.55)	0.57	
Turn left	Transition	-1.11	(-2.09, -0.04)	0.03	*
Turn right	Error	-0.76	(-1.60, 0.01)	0.07	.
Turn right	Transition	-2.09	(-3.59, -0.71)	0.00	***

Significance: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Compared to older drivers, young drivers had a higher likelihood (odd ratio = 3.98) of being in a transition state during the event. During the parking sequence, the drivers were 2.31 times and 3.35 times more likely to make an error or be in the transition state, respectively, when compared to having a foot on the brake pedal. But drivers were found to be more likely to be in the transition state during the start up sequence, when compared to the baseline.

Of interest, the drivers' heel and back positions were related to the drivers' foot placements. If the driver's heel touched the floor, the driver was 4.35 times less likely to be in transition during the event. The driver was 2.5 times less likely to be in transition if he/she had back away from the chair during the event, but this variable was marginal significant ($p = 0.60$). Foot on the brake pedal was more likely to be observed while turning. The foot was 3.03 times more likely to be on the brake during the left turn and 8.33 times more likely during the right turn when compared to being in transition. Other drivers' characteristic variables, such as the driver exercise level and miles driven per year were marginally significant, thus were included in the model. Other variables and interactions were not found significant hence were excluded.

5.6 Summary

This chapter focused on trips that only contained pedal errors and potential pedal misapplications in the naturalistic driving study. It is of interest to classify drivers pedal application types based on all information collected, including drivers' characteristics, cognitive function levels and physical body size measurements, trip characteristics and driving behavior, etc. Information such as drivers' right foot placement prior and during the error were also collected and analyses revealed that there is a relationship between these two features. Further, the analyses revealed that the parking and start-up sequence also had an impact on the likelihood of conducting a pedal error. Based on literature review, drivers in panic or a startle event is another pedal error related factor. Thus, a tight parking maneuver with a sudden event was conducted and the results are shown in the next chapter.

CHAPTER 6. DRIVER BEHAVIOR DURING AN EMERGENCY SITUATION

Pedal misapplications might be more likely to occur when drivers are startled or stressed. When the driver is startled, he/she is more likely to hit the wrong pedal in panic, or fail to respond. This study purposely placed two sudden events at the end of the controlled study, one lead vehicle braking event for the driving simulator study and one sudden horn event for the parking lot study. Several emergency braking events were observed during the naturalistic driving study as well. The research question "how do drivers respond to emergency events" is then discussed in this chapter.

6.1 <u>Summary Statistics from the Simulator Drive</u>

When responding to the lead vehicle braking event in the driving simulator study, only a few drivers hit the brake pedal without making an error. There were three types of responses (direct hits, corrected trajectories, and pedal errors) observed in the lead vehicle braking events with pedal errors being the most frequent (Figure 17). Drivers in age group 25 to 44 years old had the highest percentage (86%) of pedal errors (n=6). Drivers in age group 65-75 years old had the lowest number of pedal misapplications (n=4, 50%). Only seven participants hit the brake correctly, and six drivers hit the gas pedal first and then changed to the brake pedal. There were three drivers who pressed the brake pedal first, but then changed to the gas pedal. Due to the small sample size, there were no significant differences observed across age groups for the different response types (p=0.92, Fisher's exact test). There were no significant differences between males and females among the three response types (p=0.60, Fisher's exact test).

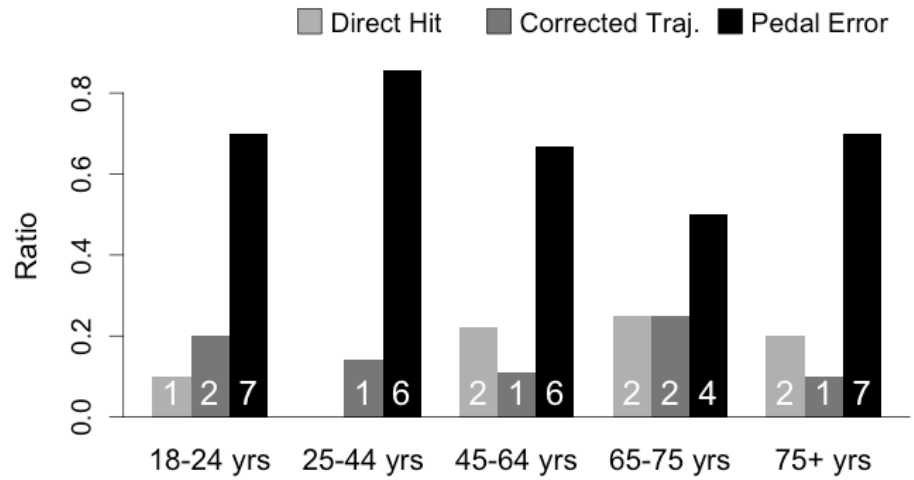

Figure 17 Frequency of Pedal Errors by Age Groups

6.2 Efference Copy

The pedal pressure duration time refers to the total time that the sensor detected continuous pressure on the pedal. Figure 18 shows the density plot of pedal pressure duration time for regular pedal applications (upper figure) and in the sudden lead vehicle braking event (lower figure). Compared to the regular braking tasks, the lead vehicle braking event generated longer pedal duration time even though many participants pressed the wrong pedal (i.e., the accelerator pedal). Since the drivers' responses (braking or accelerating) do not impact the traveling speed, it is highly possible that those participants who hit the accelerator pedal inadvertently believed that they actually pressed a brake pedal since no feedback was provided to the driver as to whether they were slowing down or speeding up. This is similar to Schmidt's "efference copy" theory (Pollard & Sussman, 1989; Schmidt, 1989) which suggests that the central nervous system may order a correct movement towards the brake pedal, but in reality, an efference copy might substitute the actual feedback from the foot with the predicted sensory feedback and give the driver the perception that he/she was on the correct pedal.

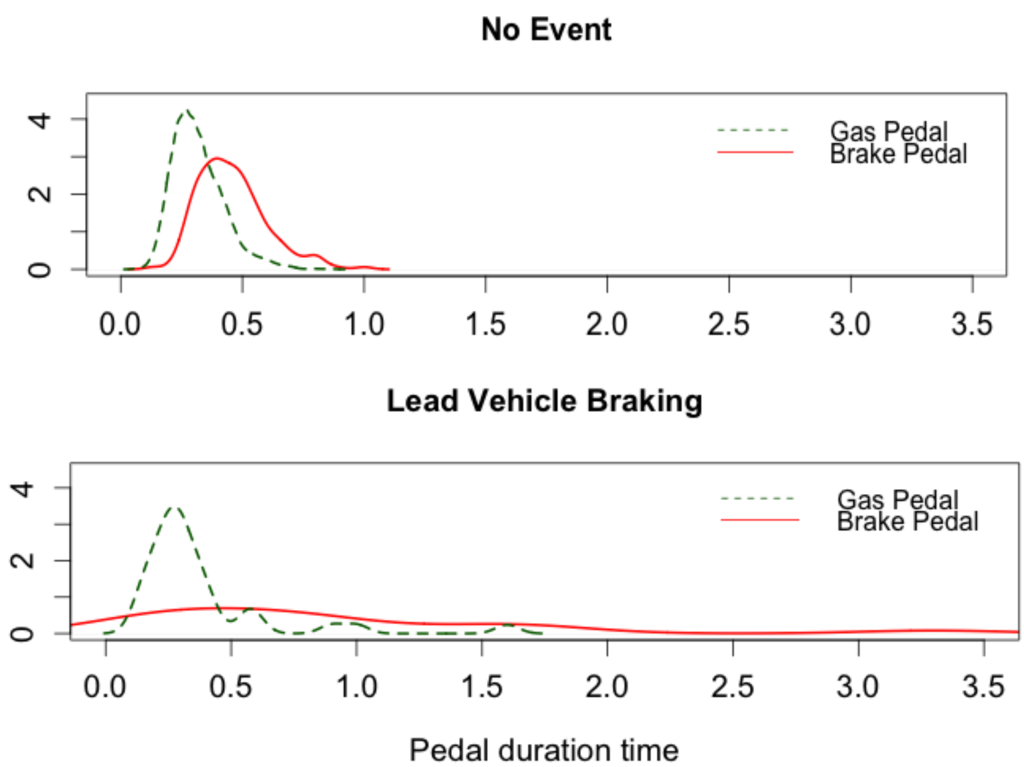

Figure 18 Density plot of pedal duration time (no event vs. lead vehicle braking event)

6.3 <u>Qualitative Summary of Emergency Braking</u>

A startle event occurred as the driver got very close to the boxes (i.e., the border of the parking spot) in the parking lot study. The startle event consisted of the sudden-onset of a vehicle's horn alarm from the driver's own vehicle. Unfortunately, no pedal misapplications were observed during this portion of the study and nobody hit the boxes. In this section, only summary information is presented of the drivers' reactions during the startle event. Among the 57 participants, 38 of them fully stopped the car during the startle event. Among those who stopped the car, 20 drivers had their hands off the steering wheel at the same time. There were seven drivers who pressed the brake but the vehicle was still in motion and among them one driver had hands off the steering wheel during the process. Twelve participants did not apply the brake pedal at all. Four of them had hands off the steering wheel and one driver turned the steering wheel a lot during the event.

In the naturalistic driving study, a sudden braking event was classified based on any longitudinal threshold exceedance of 0.6 g or higher. Only nine (9) instances of emergency braking were observed but no pedal error occurred. All but one of the events involved an older driver. All the events took place on dry, paved roads. Seven took place during the day, one at dusk, and one at night. All the drivers except one had their foot on the accelerator prior to the event. Driver's foot placement during the event resulted in six covering the entire upper portion of the brake, while the other three covered the upper, middle right portion of the brake. Table 15 shows narratives of the situations that led to the emergency braking maneuver. There were five emergency braking that had similar situations as the sudden lead vehicle braking event in the driving simulator study. But all of the participants applied brake and avoided the crash. Table 16 summarized pedal responses during emergency events for the driving simulator, parking and naturalistic driving studies.

Table 15 Situations leading to emergency braking

Age/Gender	Emergency Situation	Maximum G force
Older male	Driver hit brake hard to avoid deer running into driver's path. Driver struck deer. Talking with passenger.	0.69
Older female+	Driver hit brake hard to avoid hitting vehicle that turned into path at intersection	0.72
Older male	Driver hit brake hard to avoid missing the entrance to parking lot	0.52
Older female*+	Driver hit brake hard to avoid rear-ending vehicle at intersection	0.51
Older female*+	Driver hit brake hard to avoid rear-ending vehicle who stopped for pedestrian	0.56
Older female**	Driver hit brake hard for person on lawn mower on the other side of the road	0.50
Older female**	Driver hit brake hard for vehicle backing out of angled parking space on road	0.57
Younger female+	Driver hit brake hard on rural highway for turning vehicle. Driver distracted: putting sunglasses on	0.72
Older female+	Driver hit brake hard on residential road to avoid hitting vehicle turning into path from left	0.56

*, ** same participant

+ similar situations as the sudden lead vehicle braking event in the driving simulator study

Table 16 Summary of emergency braking

Variables		Simulator	Parking	Naturalistic
Number of emergency events (n)		44	57	9
Applied Brake Pedal (n, %)	Yes	16 (36.4%)	45 (78.9%)	9 (100%)
	No	28 (63.6%)	12 (21.1%)	0 (0%)
Response Type (n, %)	No Error	7 (15.9%)	57 (100%)	9 (100%)
	Corrected Trajectory	7 (15.9%)	0 (0%)	0 (0%)
	Pedal Errors	30 (68.2%)	0 (0%)	0 (0%)

6.4 Summary

This chapter described drivers' responses towards emergency braking event(s) in the driving simulator, parking lot study and in the naturalistic driving. Most drivers were confused by the lead vehicle braking event in the simulator scenario and some of them kept pressing the wrong pedal which could be explained using Efference copy theory. No pedal misapplication was observed during the parking lot study but a summary of drivers' reaction towards the sudden horn event was provided. Only nine examples of emergency braking were observed in the naturalistic driving study and none of them led to a pedal misapplication. A qualitative analysis on each emergency braking was provided at the end of this chapter. In the next chapter, some interesting findings, contributions and limitations of the current study are discussed.

CHAPTER 7. DISCUSSION

Prior to 1990, pedal errors were more likely to occur during the start-up sequence. But the implement of Brake-To-Shift-Interlocks (BTSI) eliminated the application of the accelerator pedal rather than the brake as a driver moves the shift lever from Park to Drive or Reverse, which reduced the number of pedal errors during the start-up procedure. However, the BTSI feature could not reduce pedal errors that occur after the transmission has been shifted into gear. There is a complex interaction between the driver, vehicle, driving tasks and driving environment. Previous studies focused on drivers' reaction times if a driving simulator was used. Other studies used the crash data, which were self-reported and did not contain information about pedal errors. There is a need to examine foot behavior systematically.

From the literature review, there were several gaps identified that could be tested in experimental and naturalistic environments. These included:

1. Fast pedal activation pace
2. Parking maneuvers, especially backing up
3. Startling conditions
4. Aging drivers

To capture the essence of these issues, three studies were developed to understand the performance issues associated with each. Video cameras were installed during all three experiments so that the foot movement could be analyzed. The detailed research questions include: (1) Do different traffic signal cues impact foot behavior? (2) What are the variations in drivers' foot to pedal movements? (3) Do foot behaviors differ in terms of context and drivers' characteristics? (4) How do drivers respond to emergency events? Statistical models were used to answer these research questions and results were shown based on algorithms such as functional data analysis (FDA), mixed effects ANOVA, multinomial logit regression with repeated measures and random forest. Interesting findings and further studies will be discussed in this chapter. Moreover, there are several concerns and limitations that must be considered in conjunction with these results.

7.1 Discussion

Pedal Applications Types from Simulator Driving Study

The emphasis of the driving simulator study was to understand foot movements on the approach to a pedal, recognizing that a pedal error is quite rare. Error rates were likely to be higher if the sequence of events was unanticipated (Philipp & Koch, 2005). This study was designed to overexpose drivers to pedal placements and foot movements while performing a sequence of accelerating and braking actions as observed in stop-and-go traffic. This study attempts to identify the foot trajectories that might be associated with pedal misapplications and tries to categorize the pedal applications types. The types of incorrect pedal applications were similar to those in other studies (Schmidt & Young, 2010; Tran et al., 2011; Young, Heckman, & Kim, 2011) but our study also included pedal types for correct applications (direct hit, hesitation and corrected trajectory). The corrected pedal movements associated with hesitation and corrected trajectory should not lead to pedal misapplications but are of interest since delays in responses may present a safety concern in the real world depending on the criticality of a timely response (Doshi et al., 2012). These pedal application types can provide additional insights on the foot to pedal movements. The foot movements were further separated into reaction time and pedal duration time for greater insights.

In the driving simulator study, participants pressed the appropriate pedal based on the color depicted from a traffic signal. However, they were not exposed to transitional periods (from green to yellow, yellow to red, etc.) as would be observed on the road. Hence, the scenarios are somewhat artificial. That said, foot to pedal changes are not discriminated visually, but are done based on blind positioning movements that are based on proprioception and kinesthetic senses. Hence, the differences in movements (corrected trajectories and pedal errors) observed are relevant to driving. When the signal was depicted to be in closer proximity to the driver (i.e., the signal appeared larger on the screen), they tended to generate a sense of greater urgency, and one would anticipate a quicker response, and our findings showed that to be the case. In such scenarios, there were more corrected trajectories as well as more pedal errors. The response time and pedal duration were both significantly longer for red signals than for green signals. For green signals, most drivers would just tap the accelerator pedal, but for red signals, drivers pressed the brake pedal for longer periods of time. But longer response time did not lead to more accurate pedal applications. The model showed that participants were less likely to have a direct hit when the signal was red. But if the participant directly hit the correct pedal for a red signal, the response time was shorter when compared to the other three pedal application types.

The youngest drivers (21 and under) were more likely to have a direct hit on the correct pedal than other age groups. This group had less pedal errors and hesitated less when executing a foot movement. Alternatively, the older and oldest age groups were more likely to have corrected trajectories compared to the youngest group. The oldest age group had a higher probability of hesitation and pedal errors. Unlike findings from the crash data (Lococo et al., 2012), this current study was designed to elicit responses that considered the participants' ability to respond to traffic lights. It is unclear whether some age groups (e.g., younger drivers) were responding to the stimuli as though the simulator driving was a video game, and it is unclear whether younger drivers would respond similarly in the real world, which is a limitation of this study. That said, the impact of age-related effects on crash risk are well documented (Kimura & Shinohara, 2012; Lococo et al., 2012; Warshawsky-Livne & Shinar, 2002) and this study may provide some insights on what transpires prior to a crash.

Foot Trajectories

Pollard and Sussman (1989) showed that pedal misapplications could be minimized if the pedals were set at different heights and distances. Schmidt (1989) also showed that the variation in the foot trajectory and end points could impact the likelihood of a pedal misapplication. The study discussed in chapter 3 showed that there were higher trajectories in direct hits when compared to slips and misses (two sub-categories of pedal errors). The functional principal component analysis was used to capture the majority of variations for the three categories of foot trajectories (direct hit, corrected trajectory and pedal error). Variations in foot trajectory height and depth were observed in all three pedal application categories. Different drivers have different mobility, hence variations in foot movements should be considered as normal. But the foot should have a comfortable reaching area that does not foster too much variability. That is, if the foot has an opportunity to go too low, the driver may slip or even miss the pedal. The reaching distance also affects the ability to depress the pedal completely.

Besides the similar patterns in foot trajectory height and depth, unique patterns were also observed from the time the driver lifts their foot off the foot-well to when they press the pedal for the three different categories. Some PC's for the pedal error showed a lot more variability in the entire pedal application procedure. That said, there was a higher variance associated with the amplitude for pedal error trajectories. The 3rd PC of direct hit, 4th PC of corrected trajectory, and the 1st, 2nd and 5th PCs of pedal error contained certain unique patterns. Further study could focus on those unique patterns of foot trajectory and factors that cause such variations could be explored and studied.

This analysis is a first step in studying variations in drivers' pedal applications, which is based on the information from trajectories of foot movement, rather than an aggregated mean or point in time. The outliers appeared to be from two categories of drivers: middle-aged females (n=2), and older drivers (n=6). This is of course a small sample, but the implications would suggest that there are some unique behaviors among these two subpopulations that warrant further research.

Naturalistic Driving Foot Behavior

The focus of the naturalistic driving study was on trips that contained pedal errors and potential pedal misapplications. Information such as pedal applications, drivers' right foot placement prior and during the error were collected and analyses revealed that there was a relationship between these features. Other independent variables included drivers' characteristics, cognitive function levels and physical body size measurements, trip characteristics and driving behavior, etc. It was difficult to duplicate the road scenario used in the driving simulator study to the naturalistic driving study. Hence, no stimuli related variable was found significant in the naturalistic driving study. But it was feasible to examine other situational variables.

The random forest predicting pedal application types performed well in this current study and allowed for feature selection. The two most important variables predicting the pedal application types were drivers' right foot placement prior and during the error. All of the drivers recovered from the error at last and no crashes occurred. In other words, the algorithm that used for predicting pedal application types was capable to predict pedal errors earlier in foot movements and gave drivers time to correct the error if an inappropriate pedal application was detected. Other variables had less importance, but they helped to improve the classification accuracy. Cognitive impaired drivers might have more pedal misapplications and this was shown by the model. Drivers' anthropometric measurements played an important role in predicting pedal application types as well, including weight, foot length, standing height and foot width. These two types of information, the cognitive function levels and physical body size measurements, could be easily obtained and feed into the algorithm developed for an in-vehicle assistance system in the future.

The most recent pedal application would impact the likelihood of making an error (Doshi, Tran, Wilder, Mozer, & Trivedi, 2012). This sequential effect also applied to the relationship between drivers' foot placement prior to and during the event. The logit regression model confirmed that, if the driver's foot was on the accelerator pedal before the error, then the driver's foot would be more likely to make an error when compared to foot on the brake pedal before the error.

During start-up sequence and parking, drivers were more likely to have foot in transition compared to on the brake during the error. Such tasks are usually more complicated, which require a combination of movements, for example, applying the pedal(s) and at the same time turning the steering wheel; or pressing the pedal, shift the gear and at the same time preform a quick scan of the outside environment. Thus, the driver might be distracted and the pedal applications was delayed (i.e., in transition). Heel touching the floor or back away from the chair would greatly decrease the chance of foot in transition. Drivers' positions could be easily monitored using a sensor and/or camera in vehicle and would help to increase the predicting accuracy. Such algorithm was an exploratory but practical move in trying to reduce the pedal error crashes. There might be limitations in the current algorithm, especially in predicting different types of pedal errors accurately. Improvements are necessary before to be used in the driver assistance systems for recovering from the pedal misapplications.

Pedal Responses in Emergency

The most pedal errors were observed in the sudden braking event in the driving simulator study representing over 68% of the responses. An efference copy might substitute the actual feedback from the foot with the predicted sensory feedback, which might cause pedal errors. In normal driving, other feedback besides the pedal itself could provide feedback that the wrong pedal is pressed. More specifically, the vehicle is speeding up or slowing down provide insights that the wrong pedal is pressed. Even if the driver could detect such errors, time is crucial and in the cases noted, the driver usually lacks the time to switch pedals. In the lead vehicle braking event, participants between 65 and 75 years old had the least number of pedal errors but the most corrected trajectories when compared to other age groups. Kimura and Shinohara (2012) also showed that older drivers had more variations in foot movements when compared to younger drivers. Pedal responses with corrected trajectories could not be considered as dangerous foot movements. But more sub-movements might lead to a delay in responses or the drivers might touch the wrong pedal while correcting foot movements in such a compact space. With regards to drivers older than 75 years old, the same conclusion as Lococo et al (2012) was observed, that risks increased dramatically. There were three drivers who pressed the brake pedal first, but then changed to the gas pedal. An explanation was these drivers were trying to catch the green signal they missed right before the lead vehicle sudden brake event. However, another explanation was that they feel they had pressed the wrong pedal so they gave a second try. In this current study, it was difficult to know what caused such behavior, but this could be explored in future studies.

There was no pedal error during the parking scenario and the naturalistic driving study. More drivers applied the brake pedal during the emergency in the parking (78.9%) and naturalistic driving (100%) compared to the driving simulator study (36.4%). Further, five out of the nine emergency braking events observed in the naturalistic driving study was very similar to the sudden lead vehicle braking event in the driving simulator study, but no errors occurred in the real world. Unlike the real world driving tasks, drivers were in a safe environment while driving the simulator or in the parking lot. Thus, this might explain why there were much more pedal errors occurred in the driving simulator study. Furthermore, there was a green signal right before the lead braking event in the simulated scenario, hence drivers were guided to move foot towards the gas pedal. But in the other two studies, there was no such misleading signal.

7.2 Contribution and Publications

Pedal misapplication is considered as an important factor in collisions. Information of pedal error incidents, especially from the driving tasks aspect, are still uncovered. Few studies have focused on the foot behavior while in the vehicle and the mishaps that a driver can encounter during a potentially hazardous situation. This study is to examine the variations in drivers' foot behavior and identify factors associated with pedal misapplications. Pedal application types were classified as (1) direct hit, (2) hesitated, (3) corrected trajectory, and (4) pedal errors (incorrect trajectories, misses, slips, or pressed both pedals). A mixed effects multinomial logit model was used to predict the likelihood of one of these pedal applications, and linear mixed models with repeated measures were used to examine the response time and pedal duration given the various experimental conditions (stimuli color and location). The results indicated that signal colors and locations were associated with pedal duration. Younger people have higher probabilities to hit the correct pedal directly when compared to other age groups. Participants tended to have more pedal errors when the signal was red. Findings from this study suggest that age-related and situational factors may play a role in pedal errors, and the stimuli locations could impact the type of pedal application. This work was accepted by the *Journal of Human Factors and Ergonomics*.

A driver's ability to judge appropriate pedal placement may be explained by two psychological theories: the Simon effect and efference copy. The Simon effect refers to the situation where response times are usually faster and more accurate when a stimulus occurs in the same relative location as the response, even if the stimulus location is irrelevant to the task. This effect is examined in a controlled study of drivers' pedal responses where the phases of a traffic signal (green and red) were designed in relationship to the brake (left) and gas (right) pedal; in a horizontal orientation. The findings suggest that drivers may take longer to response to red lights that are located on the right hand side given that the brake pedal is on the left side in vehicles manufactured in the US. Efference copy refers to the internal copy a driver has of an outflowing (efferent), movement-producing signal (such as braking). Efference copy can affect the perception physiological motor control and could potentially misguide the foot movement. That is, if the motion of pressing the gas and the brake pedal are similar, efference copy might reduce the possibility that the driver detects the error and thereby correct the pedal response. The results showed that 68% of drivers pressed and continued to press the wrong pedal during a sudden event, which suggested the efference copy effects. These two psychology theories could be used to explain the pedal errors, and more importantly, they should be taken into account when designing pedal systems. This work was submitted to the *SAE 2016 World Congress Technical Sessions*.

There was no research on drivers' foot to pedal movements. Thus, it is important to analyze the common pattern of how drivers press the pedal. There will be variations in drivers' foot movements, capturing and visualizing those variations will help to understand the nature of the pedal misapplications. The video data captured 45 drivers' foot movements and motion detection technique was applied to extract the foot to pedal trajectories from the video data. The functional principal component analysis captured the majority variations with some common movement patterns observed. Unique variations in different types of pedal response were also found. Those unique variations could help us to distinguish between different types of pedal applications. As an exploratory study, a functional k nearest neighbor algorithm was applied to classify different pedal response types. In future applications, the analysis on drivers' foot trajectory discussed in this paper could be developed as a new feature in the advanced driver assistance systems. This work will be submitted to the *IEEE ITS* Journal.

Significant results were found from the naturalistic driving study with 30 drivers. Only actual pedal errors and notable foot movement that might cause potential pedal misapplications were included in the analyses. Similar Pedal response types as in the driving simulator study were categorized based on the video data. A random forest was used to classify pedal application types given other variables, including situational variables, foot placements, drivers' characteristics, drivers' cognitive function levels and anthropometric measurements. Then, the relationship between foot placements during error and other variables were revealed using a multinomial logit model. Some factors that associated with pedal errors or foot placements were discussed. The analyses showed that a driver assistance system for automatically detecting and recovering from the pedal errors could be developed. This work will be submitted to the *Accident Analysis and Prevention* Journal.

7.3 Limitations

In the driving simulator study, participants pressed the pedal based on the color depicted on the traffic signal, but they were not exposed to transitional periods (from green to yellow, yellow to red, etc.) as would be observed on the road. The signals changed in size to simulate closer distances (large circle) to for further distance (small circle) (Goldstein, 2014). Drivers were shown to respond quicker for signals that appeared to be closer. In this current study, the participants' perceptions about the distance were not actually known and it necessarily clear whether the driver really perceived the signal to be further or closer, or if they were responding to a larger or smaller signal. However, the size of the circles was encased in a black rectangle (traffic backplate) that also changed proportionately in size to represent the proximity. Further, the study population consisted of drivers who most likely had a preconceived notion of the distance based on the size of the display (which included the entire traffic backplate). Drivers were also over exposed to multiple traffic signals within a very short period and all the participants were guided to return the foot to the floor after each pedal application (Lococo et al., 2012). Hence, the scenarios were somewhat artificial but they were essential to identify the variations in foot trajectory for such a rare event. Further, because the vehicle's velocity did not change in this study, this is an open loop control system in that no feedback is provided to the drivers after they pressed the pedal. This may have also impacted on the drivers' subsequent responses to the color changes.

In the US, most areas have vertical traffic lights displays; while a few areas mount the overhead traffic lights horizontally (for example, the Atlantic City, NJ (Wikipedia contributors, 2014a); Dallas, TX (Wikipedia contributors, 2014b); some cities in California, south Florida, Nebraska and Wisconsin, etc.). We used the horizontal traffic signal displays in the scenario as this is a replication of a Japanese study (Abe et al., 2012). The value of using horizontal displays is that there are no preconceived notions from the US drivers (who were in our study population) regarding signal location and distance.

Driving simulators have been used for many years to study a variety topics regarding driving behavior. However, there are always debates on validation of simulator studies and whether it reveals the real world driving. In the driving simulator experiment, we have noticed that a few drivers had extremely short reaction time, which were unrealistic. That was because some of the drivers might have variety degrees of expectations towards those repeated tasks. Some others studies about vehicle velocity confirmed that the outcomes from the simulators were not always the same but were consistent with the results from using the instrumental vehicles under similar conditions (Godley, Triggs, & Fildes, 2002; Yan, Abdel-Aty, Radwan, Wang, & Chilakapati, 2008). In this current study, instrumental vehicles were intended to be used to compare the results from the driving simulator and the naturalistic driving study. But it was very difficult duplicating the road scenarios in the driving simulator study in the real world. However, the results could give us the exploratory idea of why pedal errors occur and what cause different pedal responses.

The foot movements were extracted from the videos, which were 2-dimensional (x and y coordinates). In future studies, 3-dimensional data could be collected if the driver wears a tracking device and the cameras are placed in multiple places. Pedal response type classification was applied based on the splines of foot trajectories using functional K nearest neighbor algorithm. Since the pedal error category involved very different sub-categories of errors but a small sample size, the classification algorithm only focused on direct hit and corrected trajectory. This is a limitation of the current study; and it would be of great interest to gather additional data to examine the sub-categories of pedal errors (i.e., wrong pedal, slip, miss or both pedals). This exploratory model showed the possibility of predicting the likelihood of a pedal application. In this study, participants were guided to lift their foot from the floor and go to the pedal(s). After each pedal application, drivers were guided to return their foot to the floor. This procedure was designed to increase the possibility of observing a pedal error. Based on the functional principal component analyses, the majority of variations were captured when the foot was lifted from the floor. It is noted that having the foot start from the floor may seem unnatural, particularly when a driver is actively in control of the vehicle. However, as drivers adapt to more advanced in-vehicle systems such as cruise control and adaptive cruise control, a foot starting from the floor becomes a more likely scenario. Thus, the results are quite applicable to examining driver behavior in the car of the future.

The data collection for the parking lot study took place on extremely hot summer days (with temperatures over 100 °F). Thus, the engine RPM stayed very high so that the vehicle did not move without applying the brake. This meant that the drivers modulated the brake pedal rather than moving their foot back and forth from the accelerator pedal to the brake pedal during jockeying maneuvers. This was a limitation of this study that no pedal errors were observed. In future studies, integrated the experiment with an up-hill slope might help to increase the foot movements between pedals.

Missing values or delayed recordings were found during data analysis. Huge human efforts were engaged to check the validation of the data using the video. No pedal error was observed in the parking lot study and a few pedal errors were observed in the naturalistic driving study. Increasing the sample size and/or extending the study period (more than four weeks) might capture more information on foot behavior. More analyses on non-errors or potential errors were useful as the nominal foot pedal positions and movements can be better understood as a baseline. This will help future automation understand when an error is about to or is occurring.

More participants were included in our study (44 in driving simulator study, 57 in parking lot study and 30 in the naturalistic driving study) compared to other similar studies. But the participants in this study may not be representative in general since all the subjects came from the same state (Iowa State). During the experiment, we observed that there were a few elderly participants who used both feet (one for each pedal) while driving the car with automatic transmission. Between 10 – 16% of the older drivers applied the brakes with their left foot in this study; no left-foot braking was observed in anyone under 65 years old. Moreover, while designing the experiment, one of the research questions was to compare the foot movements in the driving simulator versus those in the naturalistic driving study. However, due to variations in vehicles' foot-well configurations, it was impossible to have identical placement for the foot cameras. The cameras could only be placed in similar locations in each participant's vehicle and in such a way as to not interfere with driving. Thus, the research question could not be fulfilled due to the different settings of the equipment.

7.4 Future Research

The series of studies demonstrate how to use a broad set of data collection tools to address driver performance issues associated with potential pedal misapplications. The overall findings provide detailed operational definitions of foot behavior and errors not previously studied. Many of the gaps identified in the literature were addressed, but there clearly, additional data and analyses could further clarify some of our results.

No cognitively impaired drivers were recruited for this study, though drivers' cognitive function varied among the participants. The ultimate goal of this research was to understand differences in pedal errors, and more importantly to develop solutions to minimize these errors. Solutions might relate to reinforced driver training and education (especially for those who were most likely to have pedal errors) or for the design of an advanced in-vehicle technology to help detect pedal errors beforehand and assist to control the vehicle (for instance, to reduce the velocity automatically when a pedal error is detected). Horizontal and vertical variations at the end of the trajectories were found from the functional principal component analyses. The results could also be considered for the design of an innovative pedal system, which could better account for individual driver differences. However, dramatic changes in the pedal system (e.g., a one pedal system) would include a tremendous learning curve since it would require some significant retraining (similar to typing on a DVORAK keyboard when accustom to a QWERTY keyboard, or converting from a PC to a Mac system).

There may also be differences in pedal applications based on footwear as anecdotal observations showed that high heels and sandals seem to impact the ability to directly hit the correct pedal. However, there were many footwear types observed in this study and it was not possible, given the small sample size to discern any insights. Therefore, this could be a future study topic of interest.

The database for vehicles not in traffic (NiTS) was established in recent years, which includes more information for non-traffic crashes happened in parking lots, residential areas, etc. However, it is still difficult to gather information on pedal error related crashes. Gathering pedal use information by using a checklist with law enforcement could lead to an improvement in crash reports database and transportation safety research.

Vehicle unfamiliarity has not been studied in depth because such information were not previously considered. Lococo et al. (2012) pointed out that drivers unfamiliar with the vehicle (either new owners or occasional users) were more likely to have pedal misapplication crashes. Police reports show that pedals errors associated with a rental or friend's car were overrepresented. But it was difficult to compare the different pedal designs in the rental/borrowed vehicle and the vehicle the driver typically drove. In other simulator or on-road studies, no researchers analyzed the differences between the vehicles the subjects owned and the one they drove in the study. In this driving simulator study, none of the participants had owned or driven the 2012 Toyota Camry, which may have impacted the likelihood of pedal misapplications for some groups more than others. For example, younger drivers may be able to adapt to newer vehicles easier compared to older drivers. In the naturalistic driving study, participants had to drive at least one round trip per day to be eligible to be selected. That said, all the participants drove their own vehicles and they should be familiar with their vehicles in the naturalistic driving study. But there were still potential pedal error events. Thus, subsequent studies will provide further insights on the vehicle familiarity topics.

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