Pedal Misapplication: Past, Present, and Future

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ABSTRACT

Pedal misapplication (PM) is an error in which a driver unintentionally presses the wrong pedal. When drivers mistake the accelerator pedal for the brake pedal, the vehicle experiences a sudden unintended acceleration, and the consequences can be severe. A brief history of PM is covered, and several novel studies of PM are described. The goals of these studies were as follows:

1. Identify and analyze multiple samples of PM crashes from a variety of data sources using both established and novel methods to gain new insight into the characteristics and frequency of PM crashes.
2. Use the confirmed, real-world PM crash data to develop a custom vehicle dynamics simulation and evaluate the overall potential safety benefit of a theoretical PM advanced driver assistance system.

Using an established keyword search identification method and two unique crash datasets, a PM crash frequency of approximately 0.2% of all crashes was found. These PM crashes were typically rear-end or road departure crashes in moderate- to low-speed commercial or residential areas. Female drivers and elderly drivers were more often involved in these PM crashes, which generally featured slightly lower injury severities and often involved inattention or fatigue. Anecdotally, PM crash narratives contained repeated evidence of unexpected events, driver inexperience, distraction, shoe-malfunction, extreme stress, and medical conditions/emergencies. A novel PM crash identification algorithm was developed to detect PMs from time-series pre-crash data. This algorithm was applied to a sample of crashes with event data recorder data available, and a frequency of 4.3% of eligible crashes were found to have exhibited PM behavior, suggesting that PM crashes may be more prevalent than previously thought. While the data from these crashes suggested that a PM occurred, this dataset lacked sufficient data regarding driver intention, which is necessary to confirm each crash as PMs. The characteristics of these PM-like crashes were analyzed and found to be largely similar to those of previous samples, with notable exceptions for higher proportions of male drivers, higher travel speeds, and higher maximum injury severities. More robust data from a naturalistic driving study (NDS) was acquired, and the novel algorithm was applied to all of the sample's eligible crashes. Because the NDS data contained more data elements such as driver-facing video, crashes that exhibited PM behavior were individually inspected to confirm PM. This produced a PM crash frequency of 1.1%. The characteristics of these confirmed PM crashes were investigated, but a small sample size limits the generalizability of the results. Lastly, crash data from confirmed, real-world PM crashes was used to inform a custom vehicle dynamics model into which a theoretical PM advanced driver assistance system was simulated. The effect of the accelerator suppression system on crash avoidance and mitigation was evaluated to assess its potential safety benefit, which was found to be highly dependent on system threshold values and largely underwhelming in the absence of supplemental braking. The results indicated that a system that detected PM, suppressed acceleration, and applied braking could provide a substantially higher safety benefit.

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GENERAL AUDIENCE ABSTRACT

Pedal misapplication (PM) occurs when a driver presses the wrong pedal. When drivers mistake the accelerator pedal for the brake pedal, the vehicle experiences a sudden unintended acceleration, and the consequences can be severe. A history of the controversial subject of PM is covered, and several novel studies of PM are described. In these studies, PM crashes are identified among documented real-world crashes. This is done in three phases: (1) using narratives written by law-enforcement officers or crash investigators, (2) using event data recorders, or "black boxes," that store vehicle data prior to crashes, and (3) using naturalistic driving study data, including video recordings of subjects during daily driving. These data are analyzed to develop the understanding of how often PM crashes occur and what factors are common among them. It is discovered that the frequency of PM crashes may be an order of magnitude greater than previously estimated. In the final study, real-world PM crash data is used to virtually reconstruct PM crashes and apply an advanced driver assistance system designed to detect PM, suppress the accelerator input, and reduce the severity of the crash or prevent it altogether. By simulating a wide range of system variations, we develop a sense of the feasibility of such a system's implementation and overall safety benefit.

DEDICATION

This work is dedicated to my advisor and mentor, the late Dr. Clay Gabler, who welcomed me to Virginia Tech with an unwavering confidence and encouragement that propelled me through my graduate studies.

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1.1 What is Pedal Misapplication?

From before the Second Industrial Revolution of the late 19th and early 20th centuries (during which the first automobile was produced) to today's Age of Information and Telecommunications, periodic technological revolutions have rapidly accelerated the interaction between human and machine.[1] Central to humanity's ever-increasing coexistence with technology is the development of effective controllers. An effective controller allows a human operator to harness the full capability of a technology while minimizing the potential for operator error. As systems become increasingly complex, some controllers have incorporated dedicated human-machine interfaces to help translate the intention of the operator into the output of the system and to allow the operator to monitor the performance of the system. These complex translators can utilize components such as graphical user interfaces, audio notifications, or tactile stimuli to keep the operator and system in sync. Take, for example, a student who is writing a long book report in a word processing software. As the student finishes and attempts to close the document, the sound of a bell rings from the computer's speakers and a pop-up window appears on the screen that reads "There are unsaved changes in this document. Do you want to save before closing?" with two buttons below labeled "Save" and "Close" (Figure 1).

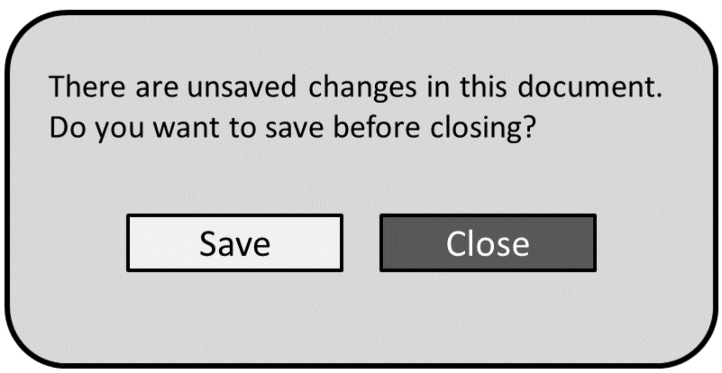

Figure 1. Exemplar graphic user interface of a pop-up window.

Here, the screen and the speakers comprise the human-machine interface, and the mouse acts as the controller. In an overwhelming majority of scenarios wherein the student intends to save their work, they will select the button labeled "Save". Occasionally, the student may commit an operator error and select the button labeled "Close". Perhaps they were in a hurry and did not read the labels correctly; or maybe their hand slipped as they grabbed the mouse, moving the cursor to the undesired button prior to clicking. Regardless, their unsaved work is lost.

Comparably, in the operation of a motor vehicle, the operator (driver) manipulates and monitors the system (vehicle) status through controls and interfaces of varying complexity. The failure of the driver to control the vehicle in a safe and prudent manner is a driver error, which has long been believed to contribute to a significant portion of crashes occurring in the United States, with some research estimates as high as 94%.[2–4] While many components of automobiles today are new or redesigned compared to those of decades past, the accelerator and brake foot-pedal control configuration (Figure 2) has remained simplistic and largely unchanged since the early 20th century.[5,6] The driver uses a foot to interface with the pedal controller and manipulate the vehicle's acceleration.

Figure 2. Exemplar vehicle control pedals.

This configuration has proven largely effective over the years, and, similar to the student saving a book report, drivers usually operate the controller to conduct the system in a manner consistent with their intentions. However, in a specific type of driver error known as pedal misapplication (PM), the driver incorrectly presses an unintended pedal. Dissimilar to the student analogy, a driver that commits a PM can be subject to far more severe consequences than rewriting a report. Accelerator-for-brake PMs (pressing the accelerator pedal instead of the brake pedal) can result in sudden unintended acceleration (SUA). If left to persist for more than a short period, an SUA can cause loss of control, crashes, injuries, and/or fatalities.

1.2 Acceleration: A Good Servant and a Cruel Master

On the afternoon of July 16th, 2003, George Weller, then 86-years-old, drove a 1992 Buick LeSabre westbound on Arizona Avenue in Santa Monica, California. Approaching a stopped vehicle at the upcoming intersection of Arizona Avenue and Fourth Street, Mr. Weller committed a PM, accelerating his Buick into the vehicle in front of him and, subsequently, into a nearby farmers' market. Continuing for approximately 10 s, Mr. Weller's vehicle traveled approximately 750 ft, killing 10 people and injuring 63 others.[7]

On the morning of February 23rd, 2021, professional golfer Tiger Woods was negotiating a curve on a roadway in Rancho Palos Verdes before traveling over a curbed median, crossing two lanes of opposing traffic, departing the roadway, impacting a tree, and rolling his vehicle (Figure 4). The Los Angeles County Sheriff's Office investigated the crash, including imaging and reviewing the data from the event data recorder (EDR), and determined that "Woods inadvertently hit the accelerator instead of the brake pedal". This high-speed road-departure crash resulted in comminuted open fractures to Mr. Woods' right tibia and fibula, among other injuries.[8]

Figure 3. Post-crash vehicle damage to Mr. Weller's 1992 Buick LeSabre.[7]

Figure 4. Post-crash vehicle damage to Mr. Woods' 2021 Genesis GV80.

These high-profile crashes serve to illustrate the potential risk that this seemingly simple error poses to public safety. This risk is not limited to passenger vehicles of Los Angeles County; between 2005 and 2008, the National Transportation Safety Board (NTSB) investigated five heavy vehicle crashes (a fire truck in Asbury Park, New Jersey, and busses in Liberty, Missouri; Falls Township, Pennsylvania; Nanuet, New York; and Newtown, Pennsylvania) and determined PM was involved in each of them.[9] These five crashes resulted in a total of two fatalities and 71 injuries. In 2015, the National Highway Traffic Safety Administration (NHTSA) issued a press release claiming that approximately 16,000 PM crashes occur across the United States every year, or 44 per day.[10] In the same year, Japan's Institute for Traffic Accident Research and Data Analysis noted between 6,000 and 8,000 PM crashes per year (approximately 16 to 22 PM crashes per day) from 2004-2013, which represented approximately 1% of all injurious accidents during that time.[11] The first objective of the current study is to expand upon past research by identifying new PM crashes, re-evaluating their frequency, and analyzing their characteristics to leverage an improved understanding of PM crashes and the risk they pose to public safety.

1.3 A Brief Look Forward

Momentarily transitioning into a solutions-oriented perspective of PM, it is appropriate to return to the book report analogy once again. Unintentionally losing unsaved work is an undesirable outcome of the human-system interaction, and the developers of the word processor may construct and implement a fail-safe to improve the user experience. This could include features such as a simple pop-up window that asks the user, "Are you sure you want to close the document without saving?" or a more complex algorithm that measures mouse cursor dynamics and attempts to evaluate whether the cursor has been accidentally bumped out of an intended position before an option is selected. For vehicle operation, these fail-safes can take the form of an Advanced Driver Assistance System (ADAS). As the name suggests, ADASs are designed to intervene to assist the driver in safety-critical situations and mitigate the consequences of driver error. For example, if a driver does not notice when a lead vehicle suddenly brakes, an ADAS known as Automatic

Emergency Braking (AEB) may recognize the potential danger and reduce the speed of the vehicle to mitigate or prevent the crash. ADASs offer an important transitional step between traditional passive safety features like seatbelts and airbags, and the conceptual safety benefits of fully autonomous fleet. The safety-related performance of various ADASs, including AEB, Forward Collision Warning (FCW), Pedestrian Automatic Emergency Braking (P-AEB), Lane Departure Warning (LDW), and Intersection Advanced Driver Assistance System (I-ADAS), have been simulated to suggest a wide range of theoretical crash and injury reduction rates for respective crash types, with some as high as 80% and 93%, respectively.[12–18] While many of these systems are in early or developmental stages, studies of field data regarding comparatively older systems, e.g., Volvo's City Safety system, have already indicated real-world, observable decreases in crash surrogates, e.g., collision claim frequency, collision claim severity, and overall losses for collision and property damage liability.[19,20] Though the benefit has understandably not yet approached estimated maximum benefits, these early findings indicate that these systems can effectively mitigate and prevent crashes and, thus, prevent injuries and save lives. This leads to the final objective for the current study, which is to evaluate the potential safety benefit of a theoretical PM crash mitigation and prevention ADAS.

Chapter 2: A History of Pedal Misapplication

2.1 Pedals Possibly Problematic

Perhaps the first authoritative mention of pedal error arises a decade following the creation of the United States Department of Transportation (USDOT) in 1966 and only a few years after the establishment of NHTSA in 1970. This 1976 NHTSA report investigated police report narratives from a North Carolina (NC) state crash database – a database that would continue to aid in the investigation of PM for the next half-century – to analyze driver-vehicle incompatibilities and their role in crash causation.[21] Specifically, Perel identified 62 crashes containing evidence of driver problems with pedal controls and concluded that there existed a need to improve the operability of such controls. This conclusion was reached despite the stated limitations of police report narrative analysis, including:

1. Narratives are inherently biased because they are based on driver statements and police observations. Drivers are not always truthful and may tend to deflect blame, while police officers focus on law violations as opposed to crash causation factors.
2. Narratives are unstructured, and there exists no strict method for writing a narrative. Therefore, it is impossible to know what was not included.
3. Poor grammar and sentence structure of police reports can prevent decisive interpretation.

"The overall impact of the above limitations on the analysis is that the magnitudes of the problems that were identified are underestimated," and, therefore, an accurate magnitude of pedal error was not determined. A year later, while conducting a driving simulator study investigating methods to reduce lag time between stimulus and braking, Glass and Suggs chose to disregard multiple experimental measurements because their subjects caught their foot on the brake pedal.[22] The authors advised, "Although no mention of this problem was found in the literature, it has been noted by the experimenters in many existing vehicles and should not be considered peculiar to the laboratory simulator". These two studies are important not only because they are some of the first recorded mentions of pedal error in a research context and cast the first light on a significant and obscured crash causation factor, but also because their organic and scientific observation foreshadowed the significant controversy and widespread media attention soon to come.

2.2 Introducing Sudden Unintended Acceleration

Many investigations that have influenced the state of PM knowledge thereafter were birthed either directly or indirectly from the phenomenon of SUA (also referred to as unintended accelerations, sudden acceleration incidents, sudden accelerations, etc.), wherein a vehicle experiences a rapid, high-powered, and unexpected acceleration accompanied by an apparent loss of braking effectiveness that notoriously gained traction among the American public in the early-to-mid 1980s. At this time, many SUA incidents were reported to occur upon initially shifting from park. In the years between 1974 and 1988, SUA had been separately investigated by NHTSA more than 100 times involving more than 20 manufacturers. A comprehensive examination of SUA was conducted in 1989.[23] One particular vehicle model, the 1978 – 1986 Audi 5000, attracted an unusually high rate of SUA complaints and was subject to a more detailed investigation that explored mechanical (e.g., the idle-stabilization system, cruise control system, transmission, and brake system) and driver-related failures which could trigger SUA (Figure 5).[24] This report proposed that: 1) a purely vehicle-based cause of SUA would require a simultaneous malfunction of engine power regulation and braking, 2) such failures should have been observable in a post-SUA vehicle inspection unless it was intermittent, and 3) if it was intermittent, it should have been reproduceable through testing.

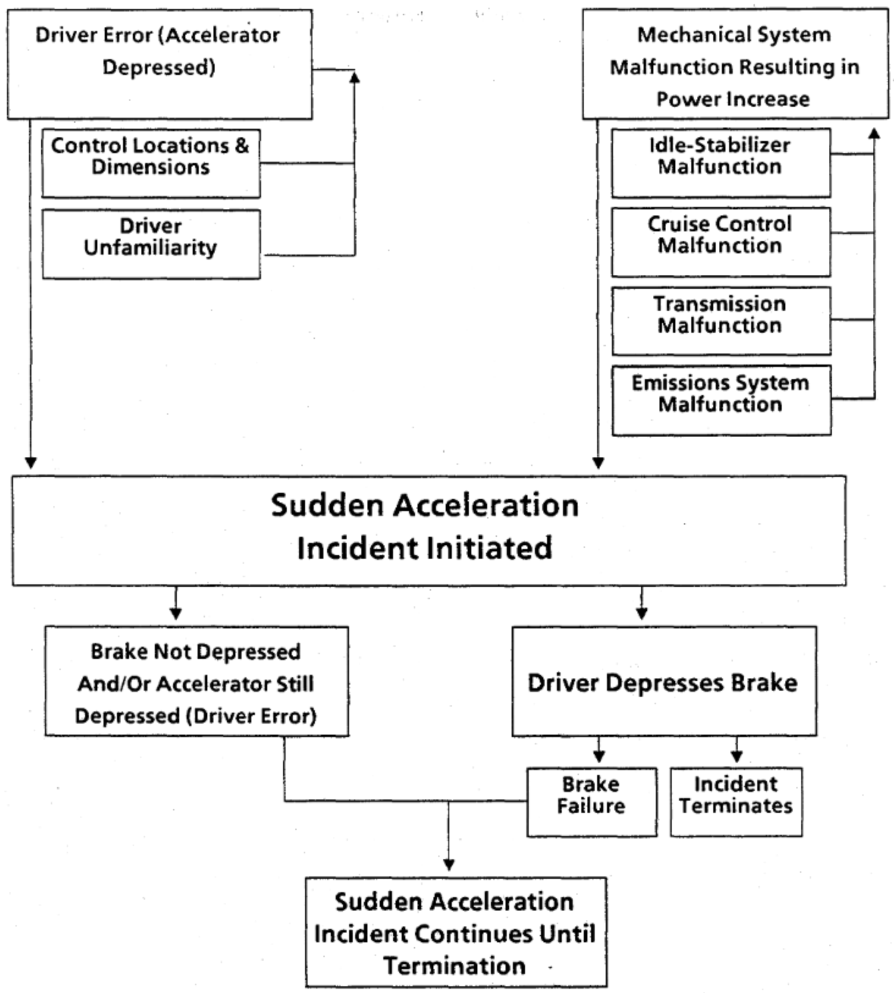

Figure 5. A driver-vehicle based SUA causation diagram proposed by Carr et al.(1988).[24]

These two studies shared many of their key findings, notably: 1) no vehicle malfunctions were found that could be the sole cause of SUA without being readily detectable in a post-SUA investigation, 2) pedal configuration may influence SUA, and 3) conditions/defects that result in excessive idle speeds could possibly startle a driver into committing a PM. With these reports, the evidence began to compile suggesting that the most probable cause of SUA was PM. Interestingly, Carr et al. also found that females reported 57.4% of Audi SUAs and that 44% of Audi SUAs involved drivers with less than six months of experience with the vehicle.[24]

2.3 The Driver Error Hypothesis

Meanwhile, the Vehicle Analysis and Simulation Laboratory at Virginia Tech conducted a study of pedal actuation errors using a driving simulator.[25] In this study, Rogers and Wierwille observed one error for every 24 foot movements. Errors were categorized into four categories varying in severity. Serious errors, including errors where the wrong pedal was pressed or both pedals were pressed simultaneously, were infrequent and were observed to occur once for every 468 foot movements. Rogers and Wierwille observed two instances where the subject committed an accelerator-for-brake PM. Outside of the driving simulator, Tomerlin and Vernoy conducted a study of pedal error in multiple, real, late-model vehicles and observed 27 total pedal errors, 15 of them accelerator-for-brake PMs that could result in SUA and one that actually did.[26] Notably, some subjects continued to incorrectly press the accelerator until they were explicitly instructed "Stop, hit the brake!". Tomerlin and Vernoy concluded, "Pedal errors apparently are more common than has been generally assumed. In most cases, drivers are able to recognize and correct such mistakes before harm results. Under some conditions when such errors are not immediately recognized and corrected, characteristic unintended acceleration may result."

Richard Schmidt's contributions to the literature of SUA began in a 1989 review article published in *Human Factors: The Journal of the Human Factors and Ergonomics Society*.[27] This article approached SUA in a new way, briefly summarizing some of the prior observational and experimental studies of pedal error and then speculating as to its potential human factor contributions. He described two categories of movement errors: higher-level response choice errors (incorrect decision making) and lower-level response execution errors (suboptimal movement performance). Because drivers who commit PMs have the intention to hit the appropriate pedal, it can be stated that PM is not an error of response choice but of response execution. Schmidt exemplified response execution errors with the acts of throwing darts and shooting free-throws. While the intention remains consistent throughout the throws, there is inherent variability, or error, in the movements. This variability causes even the most experienced players to miss bullseyes and baskets. Though the movements of throwing darts and shooting free-throws require high levels of precision relative to the movement of pressing a pedal in a vehicle, pressing a pedal is nevertheless subject to the same error principle. If the error is large enough, the foot may miss the pedal entirely. If the intention is to brake and the error is to the right, an accelerator-for-brake PM and a resultant SUA may occur. Schmidt noted two factors which influence response execution error: force generation and timing. Increasing force production increased error and, similarly, reducing movement time increased error. These principles are inextricably intertwined, as decreased time to move a set distance requires greater acceleration and thus greater force production. Applied to PM, it can be deduced that movements in emergency braking scenarios characterized by panicked, rapid foot movement toward the brake with the intention of hard, forceful brake application are subject to greater response execution error and, therefore, greater probability of PM. Schmidt also mentioned the role of negative transfer – the idea that prior driver experience with alternative pedal configurations may shape a person's expectations of a current pedal configuration – in pedal error, which may be particularly relevant for drivers with limited experience with a particular vehicle and is commensurate with the observations of Carr et al. one year prior.[24,27]

This helped shine light upon potential causation factors of pedal error, but what explanation was there for drivers who fail to recognize or correct these errors? According to Schmidt, the efference copy may be to blame.[27] Efferent signals are signals traveling away from the central nervous system. The signal from the brain that instructs the foot to press the brake pedal is an efferent signal, and a copy of this efferent signal is also sent to other sensory areas of the brain. This allows for evaluation of the performance of the movement, because the efference copy, which contains data on what was supposed to occur, can be compared to sensory signals, which contain data on what is perceived to be actually occurring. So, according to the brain, the foot was sent to the brake pedal. In the case of PM, not only does the efferent copy tell the brain that the foot was sent to the brake pedal, but the proprioception of the foot also tells the brain that a pedal was pressed. This may explain why some drivers are adamant that they pressed the brake, even when evidence suggests otherwise. Shortly after a PM, driver attention is directed toward stimuli other than that of the foot's proprioception, which may reduce the likelihood of a driver further evaluating whether the pedal that was pressed was the brake or the accelerator. The driver is drawn to the SUA of their vehicle and the upcoming obstacles to avoid. This selective attention may be exacerbated by hypervigilant and perceptual narrowing responses to the emergency situation. Schmidt provided many anecdotal references of persistent PMs, including an instance of a driver entering an aircraft parking lot, striking another car, passing through a fence, and nearly striking an airplane all in the time between PM and the detection and correction of the error. Significant latencies were also present in the aforementioned Santa Monica farmers' market crash many years later, wherein Mr. Weller committed the error for approximately 10 s and more than 750 ft.[7]

2.4 Before and After Transmission Interlocks

Between 1982 and 1987, Volkswagen of America issued four recalls addressing SUA in the aforementioned Audi models. Among them was the installation of a transmission interlock that would prevent drivers from shifting into gear without first pressing the brake pedal. This addressed the common SUA complaint in which the vehicle unexpectedly accelerates as soon as the vehicle is shifted from park. Supporting the potential safety benefit of such a system, Roush et al. observed in two 1992 studies that a substantial portion of drivers did not engage the brake before shifting.[28] Some drivers engaged both pedals with both feet, and one driver engaged both pedals with a foot rotated nearly 90˚ while shifting. According to Roush et al., "the selection of a gear with a foot located any place other than the brake affords a much higher opportunity for pedal selection error." Two years later, Reinhart cited the following points to support the PM theory of SUA causation: 1) most SUA incidents occur as the driver shifted an automatic transmission out of park, 2) manual transmission cars do not elicit SUA complaints, and 3) SUA reports have been received for all of the most common makes and models with automatic transmissions.[29] He observed a significant reduction of SUA reports among vehicles with transmission interlocks and corroborated the safety benefit of a transmission interlock among other strategies such as investigating pedal design and educating drivers.

As transmission interlocks took effect to prevent SUA while shifting into gear, the phenomenon of SUA adapted accordingly. Schmidt revisited the topic of PM in 1997 with a updated review of the NC state crash database.[30] Once again, it was concluded that PMs are a far more frequent cause of crashes than previously believed, though the numbers reported therein were underestimates still subject to the limitations of the NC crash database and the crash narrative identification method. It was unexpectedly found that only 23, or 10.5%, of 219 confirmed PM crashes occurred during parking operations as opposed to on-road driving. This finding contradicted the previously held notion that most PMs occurred while shifting out of gear and provided a possible explanation for residual SUA crashes that occurred after the widespread implementation of the transmission interlock. Interestingly, another finding of this analysis was that PMs were observed more often in an unhurried condition in which his previously theorized causation factor of increased response execution error resulting from decreased movement time may not be as applicable as previously believed. Perhaps Schmidt concluded it best, stating "These various analyses highlight the fact that we do not understand very well the processes associated with one of the most fundamental and simple movements involved in driving--pressing the feet on pedals."

2.5 Driver Age and Other Characteristics of Pedal Misapplication

Before the end of the millennia, researchers had hinted at the role of driver age in PM. In 2003, the Santa Monica farmer's market crash ignited an extensive and fervent discourse on aging drivers across the globe.[31–34] Researchers began to shift their focus accordingly, and, in the twenty years following, over a dozen studies employed a variety of methodologies to investigate and implicate the contribution of driver age to PM.[7,35–51] One of the first, a collaborative driving simulator study among Quebecois and French university research labs, observed greater motor variability in the right foot among older adults during movements from the accelerator to the brake.[35] This variability was characterized by distinct sub-movements not observed among the younger adult participants. Shortly after, Freund et al. of the Eastern Virginia Medical School found age to be a significant predictor of SUA events in a driving simulator study of 180 drivers aged 65-89 years.[36] Approximately one-third of subjects committed a PM in this study. Freund et al. blindly assessed subjects with various cognitive tests to elucidate the contributions of specific mental dysfunctions to pedal errors and found that a lifetime of daily driving experience, knowledge, and skills was insufficient in protecting the aging driver from pedal errors in the presence of executive dysfunction, i.e., impairment of the portion of the brain responsible in part for tasks such as "planning and decision-making, error correction and trouble-shooting, situations requiring novel responses and sequences of action, situations that are hazardous or technically challenging, and situations necessitating the resistance to temptation or requiring a course of action that goes against strong habitual response".[36,52] Subjects whose test scores indicated such an impairment were more than 10 times more likely to commit a PM (odds ratio = 10.04; $p < 0.0001$).[36]

Japan, the home of some of the largest automobile manufacturers in the world and the nation with the oldest population, has markedly taken interest into the crash risk of PM and the contributions of driver age.[11,53] In 2012, Kimura et al. expanded upon Freund's work by associating a more specific element of executive function, the inhibition function, to

PM using the Stroop Task and a driving simulator.[39] Inhibition is a primary executive function responsible for impulse control and temptation resistance that degenerates with age and is also influenced by stress, lack of sleep, loneliness, or lethargy.[54] Kimura et al. also observed increased reaction times among the older participants as compared to their younger counterparts.[39] Hasegawa et al. of the Japanese National Institute of Advanced Industrial Science and Technology later used a driving simulator to study the effects of driver age on PM.[48] Specifically, the effect of interruption was explored by tasking the participants to select a specific pedal while being interrupted by a touch number task. Interrupted drivers of any age group expressed a higher PM rate, with longer interruptions associating with higher rates; though, this trend was more dramatic among the older sample as compared to the younger sample. It was suggested that a decrease in memory activation for goals may induce PM.

In response to resurging SUA complaints in the 2000s, NHTSA released the results of another exploration of pedal errors in 2011 that focused on the prevalence and associated characteristics of PM crashes.[40] This work was composed of four primary studies: a literature review, analysis of media reports, a panel of driver rehabilitation specialists, and crash database analyses. The crash databases utilized were NHTSA's National Motor Vehicle Crash Causation Survey (NMVCCS) and the NC state crash database (years 2004 – 2008) because of their descriptive crash narratives. The prevalence of PM crashes as determined by the media and a keyword search analysis of the crash databases was less than 15 news-reported crashes per month or 1% of all crashes, respectively. Of course, this was provided along with the caveat that it was almost certainly underestimating the true prevalence of PM crashes due to the study's limitations. Interestingly, Lococo et al. corroborated previous findings of an overrepresentation of aging drivers in PM crashes and added that younger drivers may also be over-represented. Because the NMVCCS PM sample was small (n=31) and the news media reports were likely biased with regard to age (crashes involving younger and older drivers are more likely to be "news-worthy"), the NC crash data illustrated the age result best (Figure 6). The authors described a U-shaped curve, wherein the ratio of the percentage of drivers in PM crashes to the percentage of drivers in all crashes for each age group was greater than one for the youngest drivers (20 years or less) and the older drivers (more than 60 years), and less than one for drivers in between. It was proposed that the current hypothesis of poor executive function contributing to increased likelihood of PM in old age could just as well be applied to explain the overrepresentation of younger drivers in PM crashes, because the areas of the brain that control executive function are still developing in early adulthood.[40,55] This was further supported by observations of PMs among young drivers with executive function impairments such as autism and attention-deficit disorders.[40]

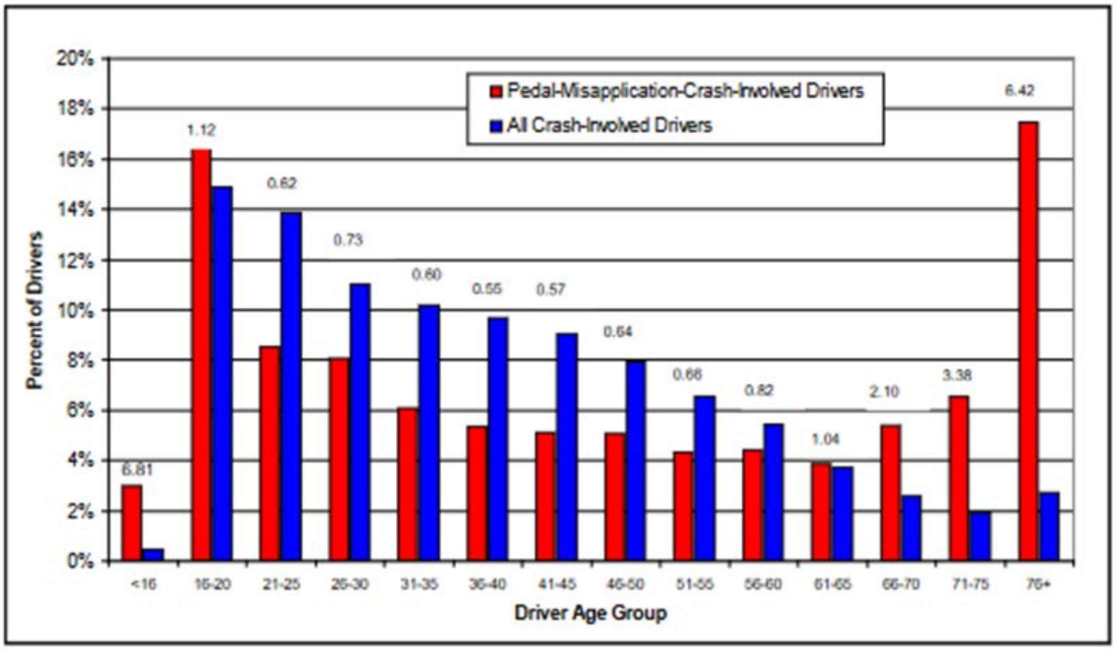

Figure 6. Distribution of age among drivers in PM crashes (n=2,399) and all crashes (n=2,228,056) in the NC state crash database (years 2004 – 2008) as reported by Lococo et al.[40]

Among few other factors, Lococo et al. explored the distribution of driver sex in PM crashes.[40] Despite an over-representation of males in all crashes, the most consistent result of this study was the over-representation of females in PM crashes, commensurate with Carr et al.'s observation from 1988.[24] The distributions were reported as 63% female in the NC state crash database, 65% in NMVCCS, and 64% in news media reports. Additionally, potential contributing factors in PM crashes identified in this study included driver inexperience, location (e.g., parking lots and driveways), inattention and distraction, medical conditions (e.g., lower-limb impairments, loss of consciousness, cognitive impairments, diabetes), driver height, and driving style (i.e., one-footed versus two-footed). PM crashes were observed in over 40 vehicle makes, with higher frequencies in more popular makes, such as Ford, Chevrolet, Toyota, and Honda. To conclude, it was noted that the problem of PM is exacerbated by the modern American communities' enormous dependence on the private automobile for activities of daily living, and the authors emphasized the need for further research to refine our understanding of pedal errors.

Separately, two research groups further analyzed each of the crash databases mined by Lococo et al. First, Padmanaban et al. investigated a larger data set of the NC state crash database (years 1994 – 2009) with over 3,000,000 crashes and produced an updated estimate for a minimum PM crash prevalence in new terms: 2.3 PM crashes for every 10,000 vehicle-years.[41] Padmanaban et al.'s results largely agreed with Lococo et al.'s regarding the prevalence of PM crashes in parking lots and driveways, the potential contribution of inattention and distraction, and an overrepresentation of older drivers and female drivers in PM crashes. However, Padmanaban et al. did not observe the same trend among younger drivers, and they further observed that PM crashes tended to occur at low speeds (almost all of them at or below 35 mph and a quarter at or below 5 mph) and result in possible or no injuries.

Jonas et al. of Exponent, Inc. broadened Lococo et al.'s NMVCCS analysis by including PM crashes that were not admitted by the driver but suggested to be PMs by the narrative.[56] This expanded the sample size to 48 weighted crashes (59 total crashes). The case weight sum of this sample approximated the prevalence of PM crashes to be around 20 per day. Comparing admitted PMs to non-admitted PMs, it was noted that females had higher rates of admission (89.2%) compared to males (78.5%). This suggests that a keyword search identification of PM crashes that considers primarily or exclusively admitted PMs will systematically over-report female involvement due to an increased probability of admission. Regarding the analyses of other characteristics, substantial variability was found across all variables which indicated to the authors that PMs can occur irrespective of them. The analysis leaves much left to be investigated in the search for defining characteristics of PM crashes and was significantly limited in that capacity by sample size.

2.6 Revisiting Sudden Unintended Acceleration and the Defect Hypothesis

The aforementioned resurgence of SUA complaints received by NHTSA in the first decade of the 2000s redirected attention to the issue in a manner akin to the 1980s. Then, it was directed at the Volkswagen Group with the Audi 5000, and now, media attention focused on the Toyota Motor Corporation and their various Toyota and Lexus models.[57–63,63–66] Among these media reports is an account of a California Highway Patrol officer driving with his wife, daughter, and brother-in-law in a Lexus ES350 that experienced an SUA.[63] The vehicle accelerated uncontrollably, reaching speeds of 120 mph before striking another vehicle, departing off the road, traveling through a fence, hitting a berm, and rolling over. Audio of the 9-1-1 call from inside the vehicle seemed to suggest that the cause of the SUA was a stuck accelerator pedal. Another driver alleged that he experienced an SUA in the subject Lexus ES350 (a loaner vehicle from a dealership) a few days earlier and reported the issue to the dealership. He claimed that he managed to regain control of the vehicle by shifting the vehicle into neutral. The resultant lawsuit settled for an amount of $10,000,000, and "Toyota did not admit liability as a part of the agreement," as confirmed by an attorney representing the dealership.[63] Further, "Toyota [had] declined to comment on the terms of the settlement." Between 2009 and 2011, Toyota issued numerous SUA-related recalls affecting approximately nine million vehicles and addressing floor mat issues that could trap the accelerator pedal in an engaged state, a "sticky" accelerator pedal that could impede the return of a depressed accelerator pedal, and various brake system defects.[57,59,67–71] In 2010, Toyota was fined $16,375,000, the maximum allowed by law, for delaying the notification of the USDOT of the defects.[37] In 2014, Toyota reached a settlement with the federal government to pay a $1,200,000,000 penalty for misleading the public and federal regulators.[65] SUA complaints prompted more than half a dozen investigations by NHTSA from 2002 to 2011, including one for which the National Aeronautics and Space Administration (NASA) was contracted to assist NHTSA in the evaluation of Toyota's electronic throttle controls.[37,72–74] These studies identified two mechanical-based defect causes of SUA addressed by the Toyota recalls, and concluded that there existed some scenarios in which the brakes could lose their ability to stop a vehicle when the accelerator was stuck in a high throttle position.[72,73] The NASA Engineering and Safety Center supporting technical assessment concluded that none of the vehicles studied were capable of organically and repeatedly producing conditions for SUA and that there existed multiple fail-safes that guarded against large throttle opening SUAs due to electronic throttle control failures.[72]

The NHTSA and NASA observations and manufacturer recalls have added evidence in support of the defect hypothesis of SUA. As this evidence compiled, the defect hypothesis became a winning argument leveraged in both civil and criminal courts in the United States. In one case, Koua Fong Lee was driving home from a religious service with his pregnant wife, father, daughter, brother, and niece when his 1996 Toyota Camry allegedly uncontrollably accelerated into two other vehicles despite his best efforts to pump the brakes.[75] The Minnesota man, who was originally convicted to eight years in prison for three counts of vehicular homicide in 2007, later had his charges vacated due to evidence of mechanical failure and a determined failure of his original attorney to provide an adequate defense. In the civil realm, an Oklahoma jury was convinced that electronic defects contributed to a 2013 SUA crash and produced a plaintiff verdict against Toyota with compensatory and punitive damages summing over $3,000,000.[76] As of 2019, Toyota has settled over 500 similar matters.[77]

While these penalties and judicial decisions undoubtedly and importantly contribute to the media coverage, public perception, and industry and government action regarding SUA and SUA research (and, as an extension, PM and PM research), it is important to note that the juries and judges who make these determinations are neither subject matter experts, nor are they compelled to make determinations based solely on science. Therefore, these determinations do not independently prove defect. However, there also exists some independent scientific research to this effect. For example, in 2020, Yougnae Lee of the National Forensic Service Daegu Institute in the Republic of Korea was requested by police to examine a single SUA case study in which video, audio, and vehicle EDR data was available for review.[78] Abnormally, this SUA occurred for approximately 105 s and the vehicle travelled nearly three kilometers. Upon review of the video, it was observed that the 34-year-old driver accelerated once a leading vehicle proceeded through a crossroad and the vehicle continued to accelerate after traversing the intersection. The driver vocally questioned why her vehicle would not slow down. She then appeared to step onto the brake pedal but eventually stepped off of the brake pedal (perhaps because the vehicle did not slow as she expected). Ultimately, the vehicle impacted a bicyclist prior to hitting a building. During inspection of the vehicle, it was noted that the front end of the vehicle including the accelerator pedal was deformed due to crash damage and the floor mat was not the original mat included with the vehicle. Specifically, the aftermarket mat was approximately twice as thick as the original. The investigators used the aftermarket mat and an exemplar vehicle to reconstruct the pedal-floor mat configuration, observing that the pedal could stick to the end of the mat in an open-throttle state. In such a scenario with insufficient braking, a vehicle could accelerate in an unintended and uncontrolled manner.

Dependent upon the defect hypothesis, consumers and consumer advocates continue to submit SUA defect petitions to be evaluated by NHTSA's Office of Defect Investigations (ODI). Most recently among them are Brian Sparks' denied 2021 defect petition alleging SUA in model year 2012 – 2020 Tesla Model S, Model X, Model 3, and Model Y vehicles.[79] This petition included 246 SUA crash allegations, and, upon review of each crash in which event data was available, it was determined by the ODI that all of these crashes were caused by PM. No evidence of fault or defect was found.

Some studies have examined alternative defect hypotheses (e.g., voltage compensation defect, cosmic ray interference) with varying degrees of scientific support and will not be discussed in detail in this literature review.[80–82] Many of them have failed to explain all of the characteristics of SUA, e.g., frequency, driver characteristics, large throttle openings, simultaneous brake failure, and absence of evidence in post-crash investigations. Additionally, many authors with prohibitive conflicts of interest have also contributed to the discussion of SUA, and these works are theoretically subject to the influence of potential financial benefit associated with proving a defect hypothesis and placing liability on manufacturers.[83] The author encourages readers to evaluate the merits and potential conflicts of interest of all works, including this one, independently and critically.

With this, the search for the true causes of SUA continues to modern day, and the importance of critically analyzing the source and weight of all elements of evidence for either theory or a combination of the theories, as well as continuing to investigate the prevalence and characteristics of these safety risks, remains as high as ever. Central to this search is to identify the proper balance between the driver error and defect hypotheses. In order to accomplish this, accurate estimates for the prevalence of either cause must be calculated. Tom Dingus of the Virginia Tech Transportation Institute (VTTI), joined by the likes of other PM researchers such as Richard Schmidt, provided an insightful perspective of PM crashes during a panel at *the 2011 Human Factors and Ergonomics Society's Annual Meeting*.[84] "Perhaps the most interesting aspect of our understanding of the "cause" of such accelerations is our tendency ("us" referring to both us a human factors researchers/experts and as lay people) to want to simplify the cause to a single factor," wrote Dingus. He later continued, "anyone who has analyzed crash data in depth knows that crashes seldom have a single cause, and even similar causal factors vary from crash to crash; even when there are many similarities… unintended accelerations occur due to a number of factors including mechanical wear, pedal design configuration, floor mat interference, and driver error."

2.7 A New Look at Pedal Misapplication

For decades, researchers relied upon evidence such as driver testimony, observations from law-enforcement officers, post-crash vehicle inspections, and driving simulator studies to evaluate the frequency and characteristics of PM crashes. For decades, conclusions from the scientific community regarding PM remained unclear and hindered by significant methodological limitation while consumers, consumer advocates, journalists, and litigators filled the silence with their own truths and mistruths. This gap begged the following question: what if there was a way to obtain knowledge of what was actually occurring in the vehicle during the moments leading up to a crash?

NTSB investigators asked themselves this very question after the 2003 Santa Monica farmer's market crash, explicitly stating, "had the accident vehicle been equipped with an event data recorder, a significantly higher level of science could have been applied to assessing and understanding the driver's behavior, as well as its contribution to this accident and the broader issue of unintended acceleration".[7] Not without their own limitations, EDRs began to penetrate the market in the late 1990s and constituted a small but growing portion of the passenger vehicle fleet in the years following.[85] These devices take the form of electronic control units – typically an airbag control module – that samples various vehicle metrics (e.g., accelerator pedal position, braking status, steering input, engine RPM, among others) during vehicle operation. The data is temporarily stored in the device's volatile memory and continuously overwritten by more recent data. In the case of an event, the most recent data is transferred to the device's electrically erasable programmable read-only memory, i.e., non-volatile memory, where it is preserved. Events are triggered when the vehicle sensors observe certain kinematic criteria, e.g., a minimum delta-V or a roll-rate threshold. EDR data elements and thresholds vary by manufacturer and went unregulated in the United States until 2012. The prevalence and standardization of EDRs was improved by 49 Code of Federal Regulations Part 563, the federal policy that regulates EDR technology in the United States, and it was estimated that, as of model year 2013, more than 90% of new vehicles in the United States were equipped with EDRs.[85,86] This unprecedented access to pre-crash vehicle status at scale has provided analysts with an opportunity to capture highly-contentious and never-before-seen side of real-world PM crashes: the driver's pedal input.

Two of the few published studies to date that have examined a collection of PM crashes by way of EDR data are those of Lehouillier et al. in 2013 and Jonas et al. in 2018.[56,87] In Lehouillier et al.'s study, 22 complaints of SUA in EDR-equipped vehicles were investigated.[87] These investigations included EDR data analysis and thorough mechanical and electrical inspections. Brake-hold tests were also conducted wherein no defects were identified and the brakes were always found to overpower the engine. Most of the complainants alleged that the driver pressed the brake pedal, not the accelerator pedal. For all but one case, the EDR recorded that the accelerator pedal was engaged for part of the pre-crash sequence, and, in more than two-thirds of the cases, the data showed that the driver never engaged the brake pedal (Figure 7). For the six cases in which the brake was depressed, half of them braked only within the final two seconds, and two of them showed simultaneous application of the accelerator and brake pedals (one of these cases was determined to be caused by floor mat interference).

	Brake						Accelerator					
Case No.	-5	-4	-3	-2	-1	0	-5	-4	-3	-2	-1	0
6	Off	Off	Off	Off	Off	Off	High	High	High	High	High	High
19	Off	Off	Off	Off	Off	Off	High	High	High	High	High	High
12	Off	Off	Off	Off	Off	Off	High	High	High	High	High	High
15	Off	Off	Off	Off	Off	Off	High	High	High	High	High	High
11	Off	Off	Off	Off	Off	Off	Medium	High	High	High	High	High
10	Off	Off	Off	Off	Off	Off	Medium	High	High	High	High	High
13	Off	Off	Off	Off	Off	Off	High	High	High	Low	High	High
16	Off	Off	Off	Off	Off	Off	Off	Low	High	High	High	High
2	Off	Off	Off	Off	Off	Off	Off	Off	Low	High	High	Medium
3	Off	Off	Off	Off	Off	Off	Off	Off	Off	High	Medium	High
7	Off	Off	Off	Off	Off	Off	Low	Low	Low	Low	High	High
18	Off	Off	Off	Off	On	Off	Off	Low	Low	Medium	Off	High
4	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Medium	High
9	Off	Off	Off	Off	Off	On	Off	Off	Low	Low	High	Off
22	On	On	Off	Off	Off	Off	Medium	Medium	Medium	Medium	Medium	Medium
1	Off	Off	Off	Off	Off	Off	Off	Low	Medium	Low	Low	Medium
17	Off	Off	Off	Off	Off	Off	Off	Off	Off	Low	Medium	Off
14	On	Off	Off	Off	Off	On	Off	Off	Off	Medium	Off	Off
20	Off	Off	Off	Off	Off	On	Low	Low	Low	Low	Low	Low
21	Off	Off	Off	Off	Off	Off	Off	Low	Low	Low	Low	Low
8	Off	Off	Off	Off	Off	Off	Low	Low	Low	Low	Off	Off
5	Off	Off	Off	On	On	On	Off	Off	Off	Off	Off	Off

Figure 7. Pre-crash EDR data from vehicles involved in alleged SUAs.[87]

The results of this study strongly suggest PM as the cause of a significant proportion – but not all – of SUA complaints. The disagreement between the driver's statements and the event data provides clear evidence to support the idea that some drivers simply do not realize or admit that they are pressing the wrong pedal. On the other hand, the results of this study also seem to implicate vehicle defect, specifically floor mat interference, as a cause of SUA – though to a much lesser extent. In every case examined, the driver believed their vehicle to be faulty and reported the incident to Transport Canada's Defect Investigations and Recalls group.

Jonas et al. found EDR data associated with four of their "possible pedal error" cases identified from NMVCCS.[56] In two cases, the claims of PM are well-supported. In the first of the two cases, the EDR data illustrated what the authors described as "fat-footing," i.e., simultaneous application of the brake and the accelerator; however, this was precipitated by a vehicle swerving into the driver's lane and was presumably not the cause of the head-on collision. Cases that involve fat-footing as a result of a reaction to an emergency braking scenario support the idea that the error associated with the response execution act of pedal pressing is increased by a reduction in movement time and an increase in force magnitude, as proposed by Schmidt in 1989.[27] Fat-footing is also an important characteristic of PMs identified via EDR data, because simultaneous application of the brake and accelerator pedals is always a PM. In other words, when looking at event data in isolation and the true intention of the driver cannot be determined (i.e., did the driver purposefully accelerate prior to the crash?), it can still be confirmed that moments of fat-footing are PMs because there is no conceivable justification for applying both pedals at the same time. This notion will be revisited in Chapter 4. The second of the two cases presented strong evidence for PM, including driver statements claiming braking, and EDR data showing significant throttle input coupled with no recorded brake pedal input.[56] The 63-year-old female driver "swerved into the parking lane and proceeded to drive up onto the sidewalk. She struck a sign and then continued down the sidewalk striking a second sign, continued on the sidewalk, crossed a residential cross street, and finally came to a rest on the sidewalk on other side of the intersection". These two pioneering EDR studies have provided an unprecedented perspective into pre-impact driver behavior in PM and SUA crashes on a small scale and serve as part of the foundation for novel applications of EDRs in these crashes moving forward.

Along with the EDR, the camera is another technology capable of providing additional and important context to crashes. With advancements in camera production in the past few decades, costs have decreased and availability has increased. As a result, cameras such as surveillance cameras and dash cams have become popular among home, business, and vehicle owners. Lee and Lee leveraged this trend to take a novel look at a small sample of camera-captured SUA crashes and analyzed them for PM involvement.[88] For example, in one case, a driver who experienced an SUA claimed that they were pressing the brake pedal the entire time. Because video showed that the brake lights did not illuminate yet post-crash inspection determined them to be functioning properly, it was concluded that the driver was not pressing the brake pedal. In this study, PMs were confirmed based on two primary criteria: the vehicle must accelerate suddenly when the driver is presented with a braking scenario, and the driver must fail to correct the initial error. Ultimately, 21 of the 27 SUA cases were determined to be caused by PM, five cases were undetermined, and one case was determined to be caused by floor mat interference.[78,88]

2.8 Recent Research in Pedal Misapplication Crash Prevention

Outside of previously proposed low-tech solutions to PM, such as driver education, evaluation, or rehabilitation; alternative pedal configurations; or Schmidt's proposed two-footed driving method, some research groups and manufacturers have begun to research, prototype, and implement more complex PM ADASs.[89] The Laboratory for Intelligent and Safe Automobiles and the Computer Vision and Robotics Research Laboratory at the University of California, San Diego have conducted driving simulator and real-world driving studies to inform a Hidden Markov Model and develop a vision-based system to predict pedal applications. In experiments limited by small sample sizes, this promisingly demonstrated an ability to predict 100% of the observed PMs 200ms in advance of the misapplication (74% at 133ms).[90–93] In doing this, they also identified additional factors that may influence PM: driver workload, sequential effects, and cue modality.[91]

As previously mentioned, Japan has a particular interest in preventing PM crashes. In 2021, the Global Legal Research Directorate of the Law Library of Congress in the United States published a compendium on the regulation of crash avoidance systems in select countries around the globe, including Australia, Canada, China, France, Israel, Japan, the Russian Federation, South Africa, Spain, Sweden, Turkey, the United Arab Emirates, the United Kingdom, and the European Union.[94] Notably, Japan was the only country to address PM. In 2020, the Japanese Ministry of Land, Infrastructure, Transportation, and Tourism with the National agency for Automotive Safety & Victims' Aid broadened the Japanese New

Car Assessment Program test procedures to include performance certifications of PM prevention systems, if requested by the manufacturer. The test procedure is as follows: “To simulate the condition of misapplication between a brake pedal and an acceleration pedal, a test car is made to approach a simulated vehicle (target), and the acceleration pedal is quickly depressed from a stopped state. At this time, whether an abrupt start or sudden acceleration is controlled to prevent a collision or to reduce damage is investigated. This test is conducted assuming two types of traffic environments: the case where a car is started in advancement condition with a vehicle in front, and the other case where a car is started in the retraction condition with a vehicle behind. Even when a collision was avoided or a collision occurred, the degree of a reduction in speed at the time of the collision is investigated, and points are awarded considering the avoidance or the degree of speed reduction.”[95] These systems are not currently required. Manufacturers who have introduced accelerator suppression systems into the Japanese market include Toyota, Subaru, and Nissan.[96–98] Most of these systems activate only at low speeds and inform the suppression algorithm with object detection data from sonar sensors. Additional advancements to PM ADAS are expected in the coming years.

2.9 Relevant Research Gap

Much still remains unknown about PM – most notably, it’s frequency. Limited datasets have previously restricted frequency estimates and characterizations of PM crashes, and further analyses leveraging more comprehensive datasets such as large EDR databases and naturalistic driving studies are needed to provide new insights. The current study will first analyze databases, new and old, with established and novel methods to augment past research on PM crash frequency and characterization.

According to Toyota, their Intelligence Clearance Sonar system has prevented approximately 70% of PM crashes, “however, new technologies needed to be developed to reduce the remaining number of accidents, including accidents in situations where obstacles are absent”.[96] The development of new PM ADASs is a challenge that requires high levels of confidence to avoid accelerator suppression in non-PM scenarios, and the primary research gap lies in identifying ADAS strategies to prevent residual crashes. As these systems are conceptualized, the potential safety benefit must be quantified to assess the system’s value. The current study will conduct this analysis on various configurations of a theoretical PM ADAS informed by data and conclusions gleaned by the above-mentioned data analyses.

Chapter 3: Identifying Pedal Misapplication Crashes by Keyword Search

3.1 Introduction

As discussed in the previous chapter, the two primary databases analyzed for PM crashes are NMVCCS and the NC state crash database. These databases contain informative crash narratives that may contain descriptions of contributing factors that are absent from the coded variables. With these narratives, researchers can hope that a description of the PM was included for PM crashes, and they can employ data mining strategies that identify some of these cases. Historically, this has been achieved by keyword search. This chapter will describe the established method leveraged to identify new PM crashes and analyze them for a wider variety of crash characteristics than ever before.[49] The results and implications of this analysis will also be covered.

3.2 Data Sources

3.2.1 The National Motor Vehicle Crash Causation Study

NMVCCS was a nationally representative crash causation study conducted by NHTSA from January 2005 to December 2007.[99] NMVCCS collected data on 6,949 crashes during that time, 5,470 of which comprised a nationally representative sample. The 1,479 remaining cases had case weights of zero and were either investigated during the first six months of data collection, i.e., the phase-in period, or failed to meet all of the inclusion criteria. The criteria a case must have met for inclusion in the representative NMVCCS sample was as follows:

- The crash must have resulted in a harmful event associated with a vehicle in transport on a trafficway.
- EMS must have been dispatched to the crash scene.
- At least one of the first three crash-involved vehicles must be present at the crash scene when the NMVCCS researcher arrives.
- The police must be present at the scene of the crash when the NMVCCS researcher arrives.
- One of the first three vehicles involved in the crash was a light passenger vehicle that was towed.
- A completed police accident report for this crash must be available.

The NMVCCS data included over 600 variables or factors related to the crash, vehicles, drivers and other persons, roadways, and environment. Of particular importance to this project, the NMVCCS dataset included the crash narrative: a written report of the crash authored by trained crash investigators, typically on the order of a few paragraphs. These narratives were based on physical evidence at the crash scene as well as interviews of police, drivers or surrogates of the drivers, passengers, and witnesses, and they focused on factors contributing to pre-crash events.

3.2.2 The North Carolina State Crash Database

The NC state crash database is a comprehensive collection of all police-reported crashes in the state of North Carolina. This analysis utilized a dataset which occurred from January 2014 to May 2020, including 1,869,886 crashes with narratives. A total of 1,678,318 crashes contained associated crash data. The data included 75 accident variables for each crash, 68 vehicle variables for each of 3,030,754 crash-involved vehicles, and 21 person variables for each of 4,171,533 crash-involved persons. The cases that had a narrative, but no data were included in the calculation of PM crash frequency, but not in the factor analysis.

Table 1. Number of observations of narratives, crashes, vehicles, and persons contained in the dataset.

	Narratives	Crashes	Vehicles	Persons
All Crashes	1,869,886	1,678,318	3,030,754	4,171,533

The NC state crash database's narratives were authored by law-enforcement officers and based on physical evidence at the crash scene as well as interviews of drivers and witnesses. These narratives were typically on the order of a couple sentences. The NC state crash database had broader crash inclusion criteria than NMVCCS. Simply, the crash must have occurred on public property and resulted in an injury, a fatality, or at least $1,000 worth of property damage. However, these criteria are not as strictly followed as those of NMVCCS – for example, some agencies choose to report crashes that occurred on private property.[41]

When analyzing these two databases, it is important to recognize that they neither represent all crashes nor identical populations of crashes. The population of crashes which these datasets represent are determined by the crash inclusion criteria. As a result of their differing crash inclusion criteria, the crashes included in NMVCCS tended to be more severe than those of the NC state cash database. Additionally, the NC state crash database tended to include crashes that occurred in parking lots and driveways, whereas NMVCCS crashes were limited to public trafficways.

3.3 Methods

The searches performed on the crash narratives were designed to replicate established keyword search methods.[40] The narratives were parsed once for a set of terms indicative of a mistake ("instead," "mistak," "inadvert," and "slip"), and again for a set of terms indicative of a pedal-related event ("pedal," "peddle," "brak," "gas," "accel"). Partial words and common misspellings were used to allow for flexibility in identifying various forms of each word. For example, "brak" identifies "brake," "braked," and "braking". The results of these searches were joined, and the cases whose crash narratives returned positive identifications of terms from each search set were exported into a new dataset designated as potential PMs (Figure 8). These potential PMs were individually and manually inspected to confirm that a PM had occurred and to identify the identifying number of the vehicle in which the PM was committed.

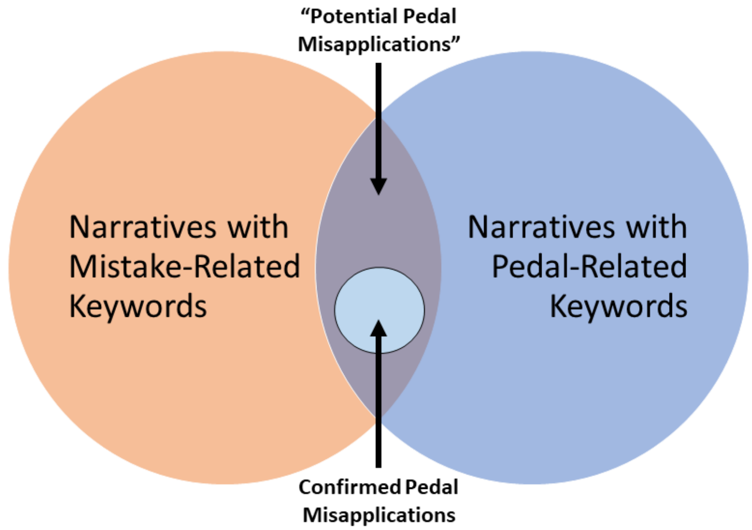

Figure 8. Venn diagram illustrating the keyword search method.

After manual inspection, the sample of confirmed PMs was created. The distributions of the PM crashes among the factors listed in Table 2 were plotted and compared to the distributions of all crashes contained in the respective database. The all-crash datasets included data on all drivers and vehicles involved in the crash, whereas the PM datasets only included data associated with the driver that committed the PM and the vehicle in which the PM occurred. Crashes that contained unknown values for particular factors were excluded from the analysis under the assumption that the distribution of the unknown data was the same as the distribution of the known data. For significance testing, a chi square goodness of fit test with $\alpha=0.05$ was performed for select factors to examine whether the distribution of PM crashes was represented by the distribution of all crashes.

Table 2. Factors analyzed from each database in the native nomenclature.

	NMVCCS	***NC***
Alcohol and Drugs	BAC Test Result	Alcohol Involvement
Date and Time	Time of Crash	-
	-	Crash Date
	Crash Weekday	Crash Weekday
Vehicle Speed	Police-Reported Travel Speed	Estimated Speed at Impact
Crash Type	First Harmful Event Crash Type	First Harmful Event at Crash Level
Weather	Weather Factors	Weather Conditions
Driver	Driver Age	Driver Age
	Driver Sex	Driver Gender
	Driver Height	-
	Driver Fatigue	-
	Driver Inattention	-
	Driver License Status	-

Crash Severity	Maximum Injury Severity	Maximum Injury Severity
Monetary Damage	-	Damage Amount
Environment	Posted Speed Limit	Authorized Speed Limit
	-	Predominant Development Type
Vehicle	Body Type	Vehicle Type

3.4 Results

3.4.1 Frequency

The keyword search produced 33 confirmed PM crashes from 110 potential PMs in NMVCCS. Twenty-six of these crashes had non-zero case weights. The confirmed PM crashes represent 0.47% of all NMVCCS cases and 0.22% of all NMVCCS case weights. The weighted cases represent approximately 5,000 real-world crashes in the United States, or approximately 2,000 crashes per year. In the NC state crash database, 9,521 potential PMs were found, of which 3,274 PM crashes were confirmed. These crashes represent 0.18% of all police-reported crashes in NC, or approximately 500 of these crashes per year.

3.4.2 Characteristics

Figure 9 and Figure 10 display the distributions of driver age among all crashes and PM crashes in the NC state crash database and, NMVCCS respectively. As expected, there was a substantial increase in the proportion of older drivers in PM crashes relative to all crashes for both datasets. Notably, drivers over the age of 74 years constituted only 7.0% in the NC state crash database and 3.7% of all crashes in NMVCCS, yet 18.2% and 22.0% of PM crashes in those datasets. Younger drivers, on the other hand, accounted for a substantially larger proportion of PM crashes than of all crashes in NMVCCS only, where drivers under the age of 25 made up 27.4% of all crashes and 34.5% of PM crashes. In the NC state crash database, the difference in PM among younger drivers was small. For both databases, p-values were calculated ($p<0.01$ for both cases). Since the p-values were smaller than the alpha level of 0.05, the null hypothesis was rejected with significant evidence to suggest that the PM crash distributions of age were not represented by their associated all-crash distributions.

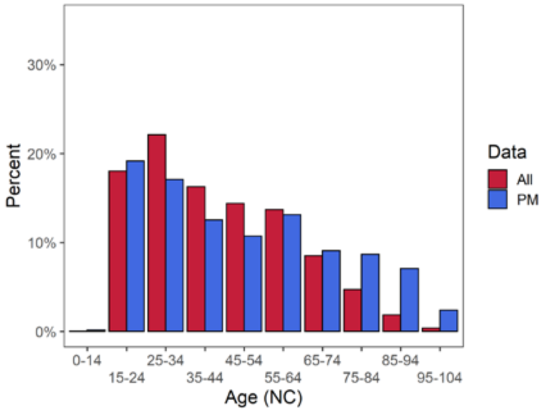

Figure 9. Distribution of driver age among drivers in all crashes and drivers that commit a PM in the NC state crash database.

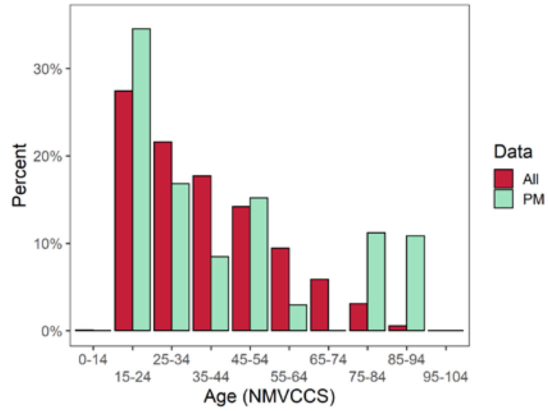

Figure 10. Distribution of driver age among drivers in all crashes and drivers that commit a PM in NMVCCS.

As illustrated in Figure 11 and Figure 12, the gender (the NC state crash database) or sex (NMVCCS) of drivers who commit a PM that resulted in a crash in both datasets was, to varying degrees, majority female, while the majority of drivers involved in all crashes among both datasets were male. PM drivers were 52.9% female in the NC state crash database and 63.8% female in NMVCCS. In a chi-squared tests for both cases, the null hypothesis was rejected with significant evidence to suggest that the PM crash distributions of sex or gender were not represented by their associated all-crash distributions ($p<0.01$ for both cases).

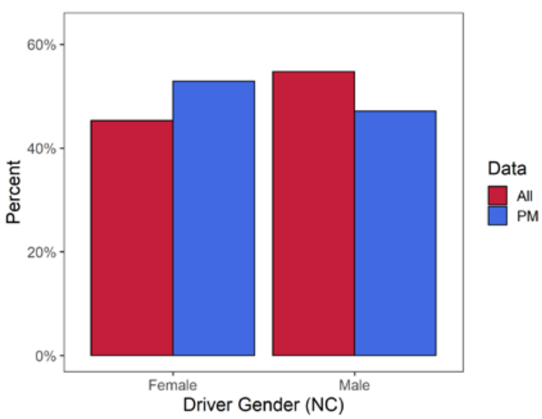

Figure 11. Distribution of driver gender among drivers in all crashes and drivers that commit a PM in the NC state crash database.

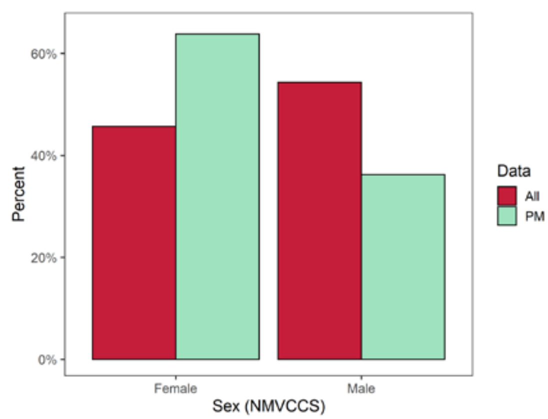

Figure 12. Distribution of driver sex among drivers in all crashes and drivers that commit a PM in NMVCCS.

Additionally, a shift towards drivers of shorter stature was observed among PM crashes in NMVCCS (Figure 13). The median driver height shifted from 170 cm to 179 cm for all crashes to 160 cm to 169 cm for PM crashes. This factor was not available in the NC state crash database.

In terms of driver license status in NMVCCS, Figure 14 shows a large increase in the number of drivers with only a permit (0.3% of all crashes, 5.2% of PM crashes) and a decrease in the number of drivers who were not licensed, or had a suspended, revoked, or invalid license. There were zero cases of the latter in the PM sample. This factor was not available in the NC state crash database.

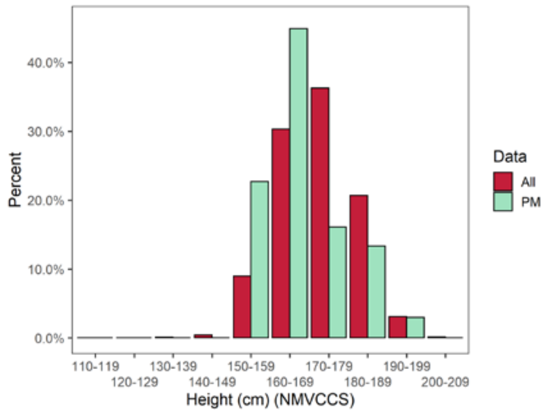

Figure 13. Distribution of driver height among drivers in all crashes and drivers that commit a PM in NMVCCS.

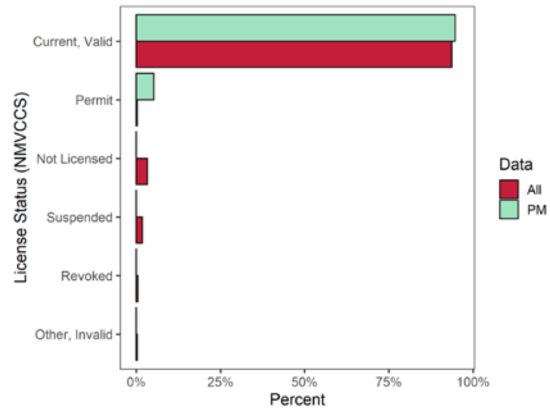

Figure 14. Distribution of driver license status among drivers in all crashes and drivers that commit a PM in NMVCCS.

Fatigue and inattention were also investigated as two factors that may correlate to PM crashes. These factors were only available in the NMVCCS database. Figure 15 and Figure 16 illustrate similar trends, wherein both fatigue and inattention were present in approximately one-in-ten drivers for the all-crash dataset and in nearly one-in-four PM drivers.

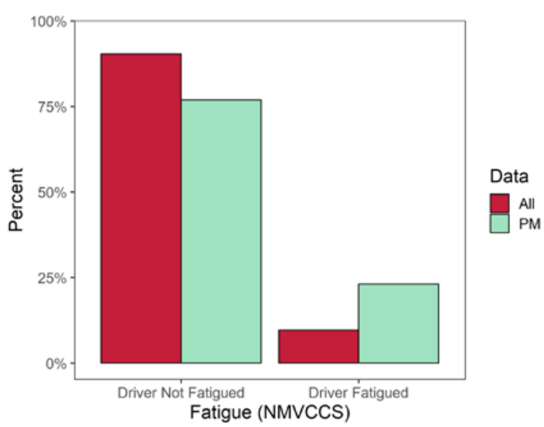

Figure 15. Distribution of driver fatigue among drivers in all crashes and drivers that commit a PM in NMVCCS.

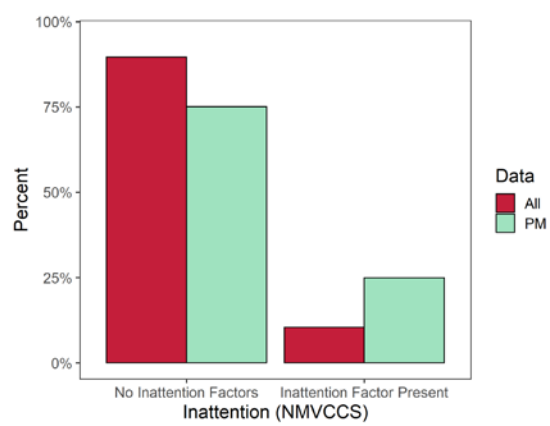

Figure 16. Distribution of driver inattention among drivers in all crashes and drivers that commit a PM in NMVCCS.

Figure 17and Figure 18 illustrate the vehicle type involved in a crash. Similar to all crashes, PMs that resulted in crashes were almost all committed by drivers of passenger vehicles (i.e., passenger cars, utility vehicles, light trucks, and light vans). The increased variability observed in the NMVCCS data was due in part to the significantly smaller sample size.

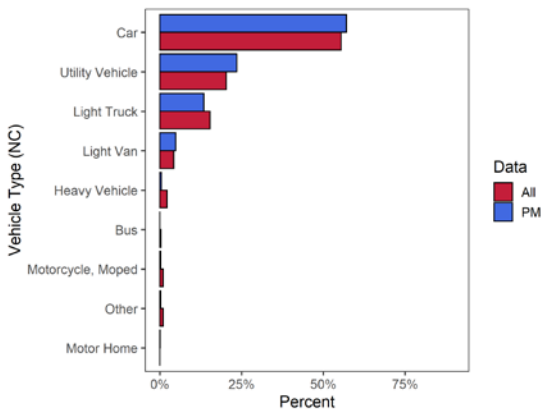

Figure 17. Distribution of vehicle type among vehicles in all crashes and PM vehicles in the NC state crash database.

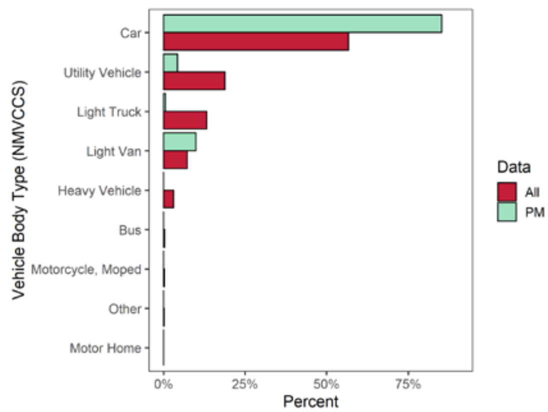

Figure 18. Distribution of vehicle type among vehicles in all crashes and PM vehicles in NMVCCS.

The role of alcohol was analyzed. The results showed a decrease in the role of alcohol among PM crashes as compared to all crashes in the NC state crash database and NMVCCS. Figure 19 shows the alcohol involvement factor for each crash in the NC state crash database as determined by the responding law enforcement officer's judgement, while Figure 20 shows the BAC test result factor for each driver from NMVCCS. These data may underscore the true prevalence of alcohol involvement.

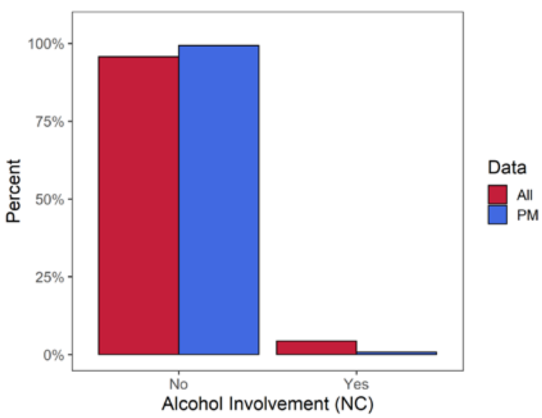

Figure 19. Distribution of alcohol involvement among all crashes and PM crashes in the NC state crash database.

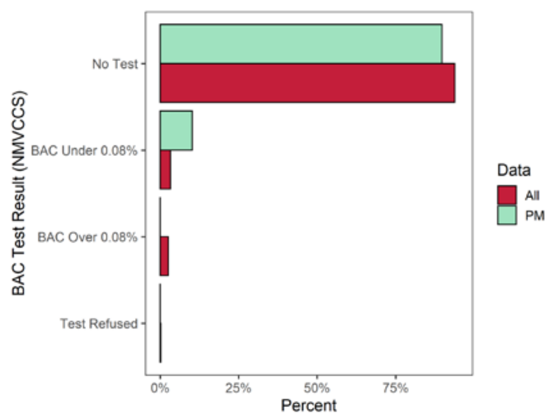

Figure 20. Distribution of alcohol involvement among all crashes and PM crashes in NMVCCS.

In both datasets, PM crashes resulted in rear-end or roadside departure crashes more often than they did not (Figure 21 and Figure 22), although the relative proportions of these two crash types were dissimilar in either dataset. In the NC state crash database, almost half of PM crashes were rear-end crashes, nearly double the proportion of rear-ends among all crashes. The proportion of roadside departure crashes was the second-largest of PM crash types and was also larger than that of all crashes. In NMVCCS, almost half of all PM crashes were roadside departure crashes, and a smaller proportion of PM crashes were rear-end crashes than of all crashes.

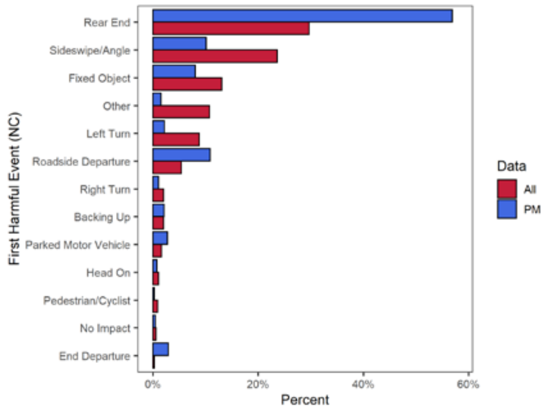

Figure 21. Distribution of crash type among all crashes and PM crashes in the NC state crash database.

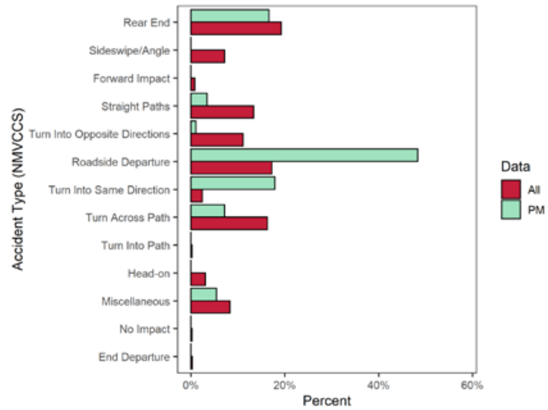

Figure 22. Distribution of crash type among all crashes and PM crashes in NMVCCS.

With regard to roadway speed limits, it was observed that PM crash settings had higher proportions of lower speed limits compared to the settings of all crashes. The NC authorized speed limit factor reported speed limit per crash (Figure 23), while the NMVCCS posted speed limit factor reported speed limit per vehicle (Figure 24).

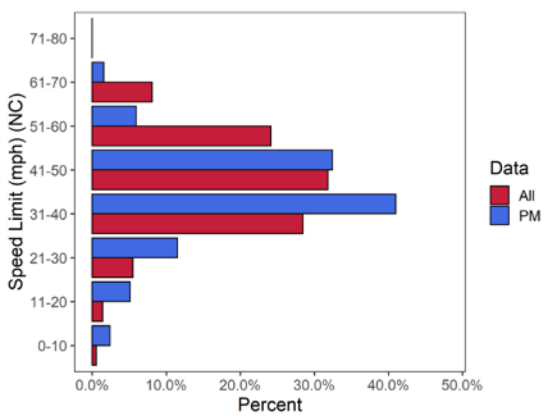

Figure 23. Distribution of speed limit among all crashes and PM crashes in the NC state crash database.

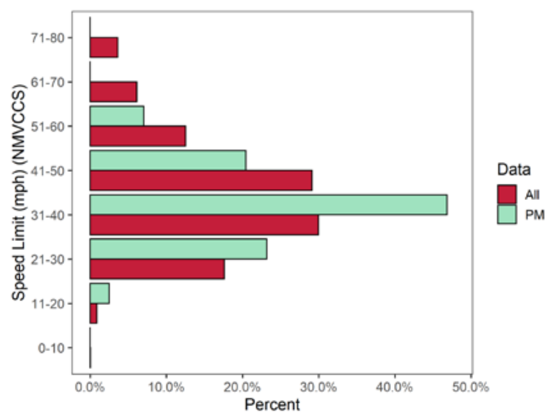

Figure 24. Distribution of speed limit among vehicles in all crashes and PM vehicles in NMVCCS.

Figure 25 illustrates that vehicles in PM crashes in the NC state crash database were typically travelling at lower speeds than those in all crashes. NMVCCS contains a similar factor; however, more than half of PM vehicle speeds and over 40% of all vehicle speeds were not reported, so those results were not further investigated.

The amount of damage caused by these crashes as estimated by the responding law enforcement officer is displayed in Figure 26. The damage amount distributions were comparable between PM and all crashes. Since crashes were only included in the NC state crash database if they resulted in an injury, a fatality or damage over $1,000, damage from $0 to $1,000 was underrepresented for both PM and all crashes.

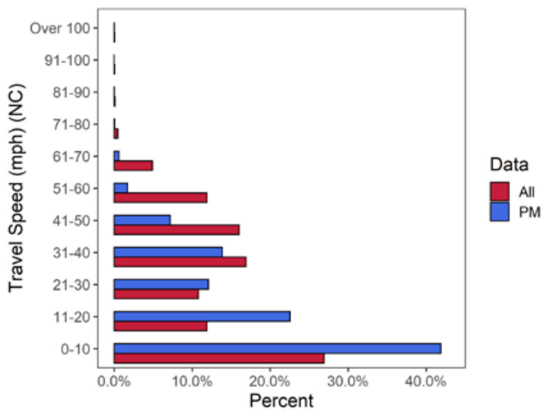

Figure 25. Distribution of estimated travel speed among vehicles in all crashes and PM vehicles in the NC state crash database.

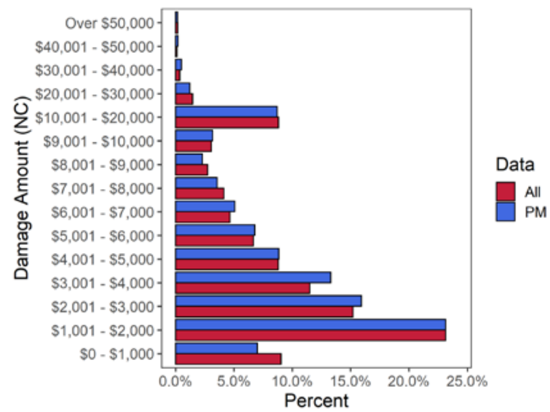

Figure 26. Distribution of damage amount among all crashes and PM crashes in the NC state crash database.

PM crashes in the NC state crash database had higher proportions of commercial and residential crash settings (over 90% combined) compared to all crashes. Figure 27 illustrates that rural settings (i.e., farms, woods, pastures), which constituted approximately one-quarter of all crashes, made up less than 5% of PM crashes.

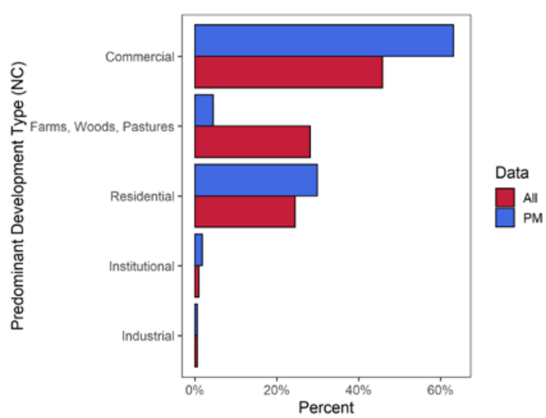

Figure 27. Distribution of estimated crash location among all crashes and PM crashes in the NC state crash database.

PM crashes in these datasets were also characterized by fewer fatalities. Figure 28 and Figure 29 display the maximum injury severities for PM and all crashes for the NC state crash database and NMVCCS, respectively. As mentioned before, the NC state crash database includes crashes that involve only property damage if it amounted to more than $1,000. Thus, the increased proportion of crashes that have no injuries as compared to NMVCCS was, in part, a result of the crash inclusion criteria. In both datasets, higher proportions of possible injuries and lower proportions of fatalities, incapacitating injuries, and non-capacitating injuries were observed.

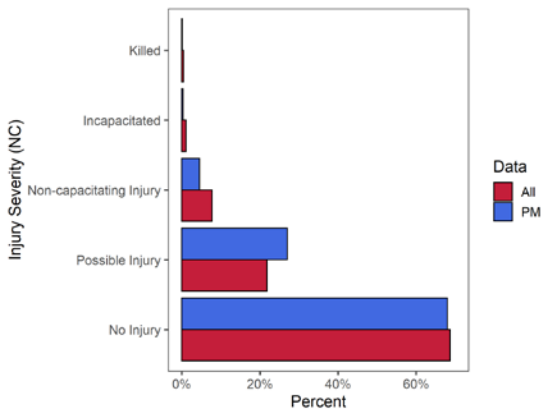

Figure 28. Distribution of maximum injury severity among all crashes and PM crashes in the NC state crash database.

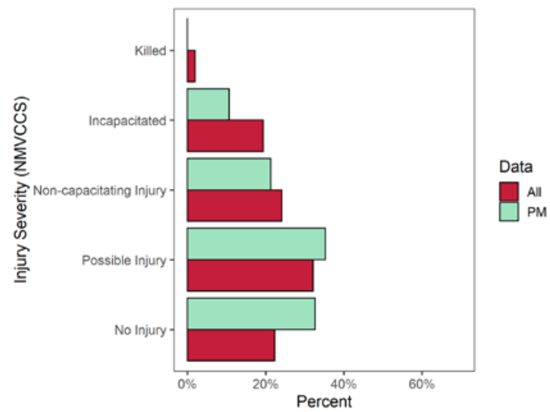

Figure 29. Distribution of maximum injury severity among all crashes and PM crashes in NMVCCS.

The proportions of these crash settings that had adverse weather conditions present at the time of crash were investigated. Figure 30 shows that weather was slightly less frequently a factor in PM crashes than in all crashes in the NC state crash database. Similar results were observed in NMVCCS (Figure 31), with a slightly higher proportion of adverse conditions (all factor levels except clear and cloudy) among PM crashes.

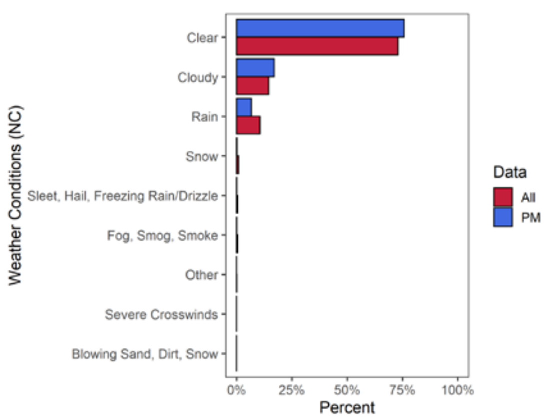

Figure 30. Distribution of weather conditions among all crashes and PM crashes in the NC state crash database.

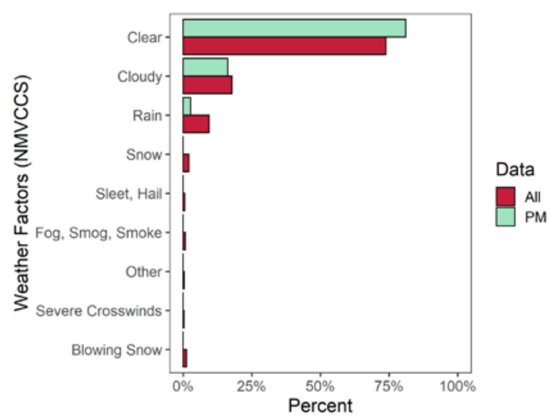

Figure 31. Distribution of weather conditions among all crashes and PM crashes in NMVCCS.

The largest proportions of PM crashes in NMVCCS occurred during the hours of 14:00, 07:00, and 18:00 (Figure 32). The largest increases in proportion relative to all crashes were during the hours of 14:00, 07:00, and 23:00.

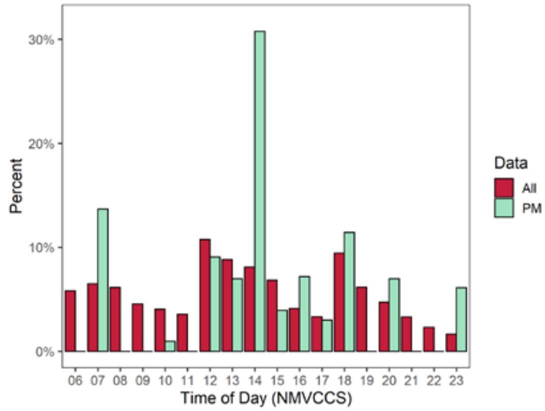

Figure 32. Distribution of estimated crash time (hour) among all crashes and PM crashes in NMVCCS.

In the NC state crash database, crash date was examined (Figure 33) and, from crash date, crash weekday was derived (Figure 34). To better visualize the distribution of crash date, a 28-day rolling average was calculated and superimposed onto the chart. The decrease in crash rate from March 2020 to the end of the data range was likely due to reduced travel induced by the COVID-19 pandemic. The distribution of crash weekday illustrates that there was no substantial difference between the proportion of all crashes and PM crashes on any given day of the week.

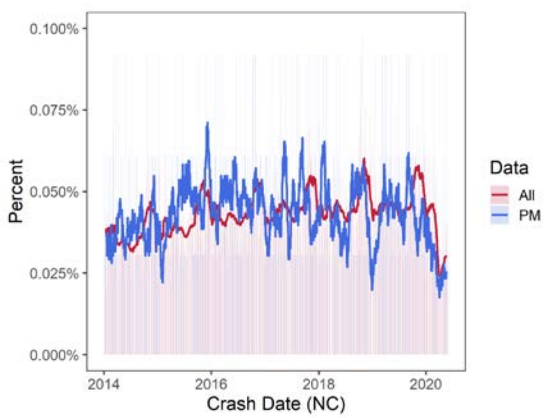

Figure 33. Distribution of crash date among all crashes and PM crashes in the NC state crash database.

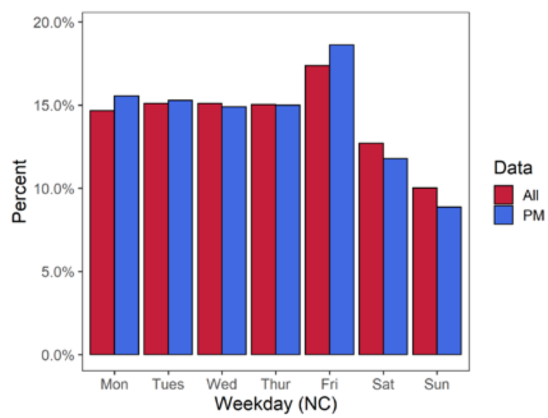

Figure 34. Distribution of crash weekday among all crashes and PM crashes in the NC state crash database.

The overarching objective of PM crash characterization is to determine the reason behind the error so that potential countermeasures can be developed. While there is not yet a comprehensive understanding as to all of the reasons why drivers press the wrong pedal, some anecdotal factors and explanations associated with PM as described in the crash narratives during the manual inspection of potential PMs were observed (e.g., "the driver claimed that they pressed the accelerator instead of the brake because …"). Many of these explanations come from the NMVCCS sample of PM crashes because the NMVCCS narratives were typically much more comprehensive than those in the NC state crash database. Repeated factors and explanations associated with PM crash narratives are as follows:

- unexpected events, e.g., car pulling out in front, leading car braking suddenly, animal in the road;
- distraction, e.g., spilling coffee, trying to tie a shoe, looking at cell phone, sneezing, stop-and-go traffic, looking back at occupants;
- shoe malfunction, e.g., flip-flop falling off, difficulty distinguishing pedals with large boots, objects caught under feet, shoes getting caught, shoe slipping off one pedal and onto another;
- inexperience or unfamiliarity, e.g., inexperienced drivers of all ages, drivers who are unfamiliar with a vehicle that they do not drive regularly;
- extreme stress or recent trauma, e.g., car radio stolen from the parking lot of the funeral home in which they were planning the funeral of their late mother, upcoming retirement, the well-being of a sick friend, an incomplete recovery from a recent heart surgery, a relative who almost drowned in a recent kayaking accident;
- medical conditions or emergencies, e.g., leg spasming or cramping, choking, vomiting, anxiety attack, feeling sick or dizzy.

3.5 Discussion

The prevalence of PM crashes nationally was estimated to be at least 0.22% of all NMVCCS-qualifying crashes. The prevalence of PM crashes in NC from January 2014 to May 2020 was estimated to be at least 0.18% of all police-reported crashes. As with previous keyword search studies of PM crashes, these values are almost certainly underestimates of the true PM crash frequency for the reasons described in the following section.[24,27,30,38,40,41,56]

Drivers involved in PM crashes were characterized as more likely to be older than 74 years old and female than their all-crash counterparts. Evidence suggested younger drivers may also have an increased PM crash rate in NMVCCS, although these results were not corroborated by the NC state crash database analysis. Therefore, this analysis partially supports the results presented in past literature.[40,41,56] It is possible that the lower proportion of PM crashes among young drivers observed in the NC state crash database was a result of the state's adoption of a graduated licensing system, which has been shown to reduce young teen crash rates.[100] PM drivers were also more likely to be of shorter stature, fatigued, or inattentive, carry a permit instead of a license, and driving passenger vehicles. Sex and age likely confounded with height in NMVCCS, as females and younger people are generally shorter. It was possible that these populations experienced higher rates of PM crashes because of a suboptimal fit within their vehicle resulting in an imperfect access to the pedals. Age and license status in NMVCCS may also be confounded, as younger drivers are more likely to only have a permit.

PM crashes were characterized as majority rear-end and roadside departure crashes, although the relative proportions of either are not clear. The disparity in the proportions of rear-end and roadside departure crashes between the two datasets is possibly explained by the crash-inclusion criteria of the NMVCCS (must have occurred on a public trafficway, one passenger vehicle must have been towed due to damage, etc.). It is likely that many PM rear-end crashes did not meet these qualifications and were not represented. PM crashes have also been characterized by similar damage amounts, and slightly lower crash severities relative to all crashes. The maximum injury severity in these crashes was less likely to have been a fatality, incapacitating injury, or non-capacitating injury, yet more likely to have been a possible injury. This result may not be entirely representative of PM crashes, though. Fatally injured or incapacitated drivers would have been less likely to be able to self-report their PM to the investigator, so those crashes would have been less likely to be written in the narrative, identified as a PM, and included in this analysis. Vehicles involved in PM crashes occurred at lower speeds than those in all crashes.

The locations of these crashes were characterized as overwhelmingly commercial and residential areas, often having slightly lower speed limits and marginally better weather than that of all crashes. Lower travel speeds follow from lower speed limits and relate to the business areas and neighborhoods where these crashes tended to occur.

Almost a third of these crashes in NMVCCS occur between the hours of 14:00 and 15:00. The next two most frequent times of these crashes, early in the morning and early in the evening, matched the patterns of the typical work-day commute. The hours with the greatest increase in proportion of PM crashes as compared to all crashes are early morning and late at night, suggesting a possible relationship with fatigue. As for crash date and weekday, the 28-day rolling average of PM crash proportion was similar to that of all crashes and PM crashes appeared to be as indiscriminate towards day of the week as all crashes.

Anecdotally, it was noted that some PM crashes occur as a result of unexpected events, driver distraction, shoe malfunction, driver inexperience or unfamiliarity with the vehicle, extreme stress or recent trauma, and medical conditions. While weather was not observed to be particularly characteristic of PM crashes in general, many narratives indicated that a foot slipped from one pedal and onto another because the sole of the shoe was wet. Weather, and rain in particular, may show a stronger effect in a subset of pedal slips.

As a whole, a likely confounding variable is traffic. Not only is a misapplication of the accelerator more likely to result in a crash when there are more vehicles around, but a driver is also more likely to be stressed, distracted, and fatigued, particularly during a rush hour before or after a long working day. Additionally, there is more traffic in commercial and residential areas as compared to rural areas, and higher traffic often reduces travel speed.

3.5.1 Limitations

The analysis was limited by the inclusion criteria of the respective databases. For example, a crash which occurred on private property or one which resulted in no injuries or fatalities and damage of less than $1,000 may not have been included in the NC state crash database. Likewise, a crash which occurred in a parking lot or did not require an EMS to be dispatched or a passenger vehicle to be towed would not have been included in the NMVCCS dataset.

The narratives were written by crash investigators or law-enforcement officers using available evidence, such as driver and witness statements. Therefore, the identification of

PM from the narrative was limited by the reliability of the statements and the inclusion of those details in the narrative by the author. If the driver did not realize or admit to the PM, it would not have been captured. If the author of the narrative decided not to include those details in the narrative, it would not have been captured. Also, since PMs are self-reported, the probability of identification in crashes in which the driver is fatally injured or incapacitated is reduced.

The keyword searches identified every case that matched the chosen keywords as written. It was possible that cases which described a PM with uncommon language, abbreviations, or egregious misspellings were not captured by the search. Each of the above limitations had the potential to cause the observed prevalence of PM crashes in each dataset to underestimate the true PM crash frequency of each population. Recent advancements in crash narrative analysis have included the application of natural language processing to crashes suspected of PM.[101] This application saves a substantial amount of time spent on manual inspection and could allow for the use of larger datasets that would otherwise be unfeasible to analyze.

The primary limitation of the NMVCCS analysis is that it contained only a small sample size of PM crashes (n=33). After eliminating cases with case weights of zero, the sample size became even smaller (n=26). Sample size was further reduced on a per factor basis by eliminating cases wherein the factor was unknown under the assumption that the distribution of the factor among the unknown crashes was equal to that of the known crashes. A minimum sample size of 20 cases was used for analysis of driver fatigue. Further details regarding sample size per factor can be found in Table 17 (the NC state crash database) and Table 18 (NMVCCS), included in the appendix.

The conclusions drawn from the NMVCCS data and the comparisons made between the two datasets are also limited due to the age of the NMVVCS data. The NMVCCS was conducted from 2005 to 2007 while the NC state crash data was observed between 2014 and 2020. This study assumed that PM crash frequency and characteristics have not changed dramatically over this time.

3.6 Conclusions

The keyword search parsed through millions of crash records from the NC state crash database and NMVCCS, and nearly 10,000 crashes were manually inspected to confirm over 3,000 PM crashes. These crashes were analyzed for 26 factors hypothesized to correlate with PM and were compared to the set of all crashes from their respective datasets. This analysis updates and substantiates some of the findings of previous research, as well as introduces many new factors never previously analyzed with respect to this unique crash phenomenon.

Chapter 4: Identifying Pedal Misapplication-Like Crashes with Event Data Recorders

4.1 Introduction

Since PM is not coded directly into any crash database at this time, identification of PM crashes poses challenges. Previous studies identifying PM crashes have largely relied on search algorithms to parse through crash narratives for PM keywords or phrases.[24,27,30,38,40,41,56] These crash narratives were written by crash investigators or law enforcement officers and can range from a single sentence to a few paragraphs. With so few words, it is often impossible to determine whether a crash involved a PM. The specific details of the narrative are included at the author's discretion and often rely on driver or witness statements. This method of PM identification poses significant limitations and underreports the true frequency of PM crashes by excluding cases where a driver does not admit to or realize that they have misapplied a pedal. Reasons why drivers may not volunteer this sort of information include self-enhancement bias (e.g., "I am too skilled a driver to have pressed the wrong pedal.") or a fear of repercussion (e.g., "If I admit my mistake, I may be held responsible for this crash.").[102,103] Likewise, even in cases where the evidence indicates a PM, the author of the narrative can choose to omit those details, misspell keywords, or describe the PM in uncommon language, all of which could result in the case being missed by the search algorithm. Even at its best, this method particularly underreports severe PM crashes, since incapacitated or fatally injured drivers are not immediately available after the crash to indicate as to whether they misapplied their accelerator.

Unlike crash narratives, EDRs collect an objective and crucial set of measurements that provide perspective into the status of the vehicle during the seconds leading up to a crash. These measurements include vehicle crash characteristics, e.g., vehicle speed, brake and/or accelerator pedal application. EDRs are constantly measuring vehicle metrics, temporarily storing the measurements, and then overwriting them with new data. In the event of a crash, the EDR locks in the most recently measured values and records additional metrics during the crash pulse. The purpose of this study was to use EDR data to develop a novel method for the identification of PM crashes that is independent of the crash narrative.

4.2 Data Source

The data source for this analysis was the National Automotive Sampling System Crashworthiness Data System (NASS/CDS). The NASS/CDS database was built from a stratified probability sample of police-reported crashes in which where one or more vehicles were towed due to damage.[104] It was a nationally-representative, in-depth crash dataset, including 63 accident variables for each crash, 126 vehicle variables for each vehicle, 104 occupant variables for each person in the crash, and brief narratives. Because it was a nationally-representative sample, the calculated case weights could be used to estimate annual national frequencies. Most importantly, NASS/CDS also contained EDR data from the involved vehicles, if available. This study considered crashes from 1997 to 2015 for which EDR data was available.

To confirm that the event stored on the EDR was the event of interest, only events that occurred during the most recent ignition cycle and involved either airbag deployment or a minimum delta-v of 8 kph (5 mph) were investigated.[85,105] For crashes in which multiple eligible events existed, only the earliest event was included. This prevented multi-event crashes from being overrepresented and prevented secondary events that could have recorded PMs that resulted from post-crash occupant movement from being included. Further, each EDR must have recorded specific metrics in order to identify PM crashes: accelerator pedal position and vehicle speed, and cases that did not include these metrics were not considered. Beginning with 82,755 cases in NASS/CDS (1997 – 2015), the number of eligible cases was reduced by the addition of each constraint, as shown in Table 3. The bottom row displays the number of cases and weighted cases that satisfied all of the constraints, i.e., the eligible population.

Table 3. Number of cases and weighted cases that met the inclusion constraints.

Selection Criteria	Cases	Weighted Cases
NASS/CDS 1997-2015	82,755	43,623,355
Contained EDR Data	14,605	7,731,208
Accelerator Pedal Position Data Available	3,365	1,732,797
Speed Data Available	3,321	1,715,653
Crash Delta-V or Airbag Deployment Data Available	2,787	1,468,425
Ignition Cycle Data Available	2,674	1,403,794
Airbag Deployment or Delta-V ≥ 8 kph	1,650	819,889
Latest Ignition Cycle	1,619	804,059
Remove Multiple Events	1,525	770,628
Eligible Crashes	**1,525**	**770,628**

4.3 Methods

4.3.1 Pedal Misapplication-Like Crash Identification

PMs are defined based on the intention of the driver to press the brake. Past studies have shown that PMs are observed in scenarios where braking is required, and many PM crashes have been triggered by unexpected events.[40,49,88] It has also been theorized that rapid, forceful foot movements such as those involved in panic braking are subject to greater response execution error and, therefore, greater probability of PM.[27] Thus, it follows that many drivers in pre-crash scenarios that commit a PM will press the accelerator pedal hard, thinking that it is the much-needed brake pedal. From the eligible crashes identified above, a strategic filter was applied to isolate crashes that contained evidence of a PM. Specifically, the time-series accelerator pedal position data was used to calculate an accelerator application rate that could be used to isolate hard accelerator pedal applications.

Additional filters were applied to reduce the occurrence of false positives identified by the accelerator application rate criteria and improve the specificity of the algorithm. These filters eliminated from consideration scenarios in which hard accelerator applications would be expected (i.e., accelerating from a full stop, accelerating in or around intersections and interchanges) and considered only crash types that either 1) comprised the majority of previously identified PM crashes (roadside departure and rear-end crashes) or 2) would logically follow from an SUA (end departure, backing, and forward impact crashes).

4.3.2 Event Data Analysis

For the EDR analysis, the moment of PM was defined to occur at half the sampling period before the first observation of an accelerator pedal application rate (also referred to as stroke rate) of at least 25% per second (%/s). For example, if accelerator position increased from 0% at 1.5 s pre-crash to 77% at 1.0 s pre-crash with a sampling frequency of 2 Hz, the time of PM was estimated as 1.25 s pre-crash. This minimizes the temporal error in the PM time estimation since the pedal was misapplied at an unknown point between these two samples. The vehicle speed at the time of PM was linearly interpolated from the bordering measurements. Similarly, the time of impact was calculated in the same manner. Most EDR modules recorded only the last measurement in the cycle and no measurement at the specific time of impact. This meant that the time of impact was within one sampling after the last measurement. If the EDR did not record the specific time of impact, the time of impact was estimated to occur half of the sampling period after the most recent measurement, and the speed of the vehicle at impact was linearly extrapolated from the previous two recorded measurements. Table 4 and Figure 35 show these calculations being performed on an exemplar pre-crash dataset.

Table 4. Example point of exemplar PM interpolation and point of impact extrapolation (NASS/CDS Case ID: 2009-43-10).

Time Point	Time Pre-crash (s)	Speed (kph)	Accel. Pedal Position (%)
1	-2.50	59.6	17
2	-2.00	59.6	16
3	-1.50	58.0	0
4	-1.00	54.7	77
5	-0.50	80.5	0

Time Point	Time Pre-crash (s)	Speed (kph)	Accel. Pedal Position (%)	Accel. Pedal Application Rate (%/s)	Point
1	-2.50	59.6	17	--	--
2	-2.00	59.6	16	-2	--
3	-1.50	58.0	0	-32	--
3.5	-1.25	56.4	--	--	PM
4	-1.00	54.7	77	154	--
5	-0.50	80.5	0	-154	--
5.5	-0.25	93.4	--	--	Impact

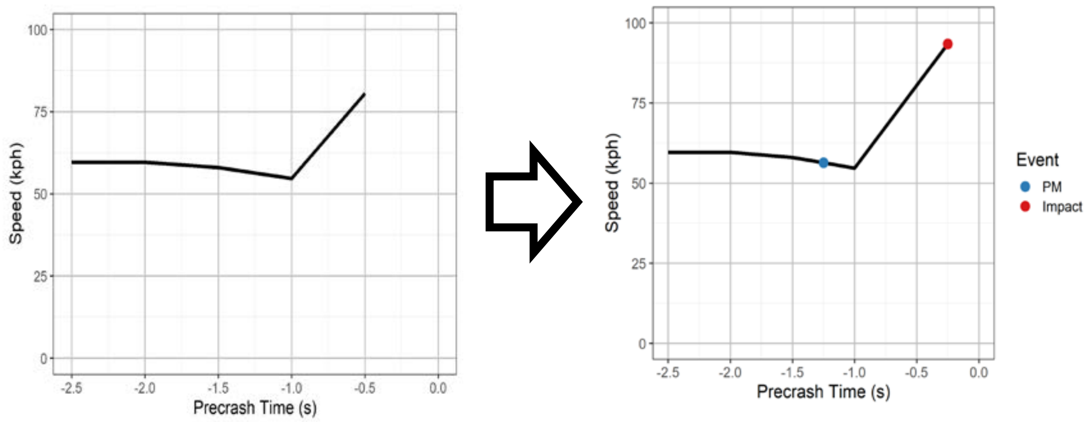

Figure 35. Graphical illustrations of point of exemplar PM interpolation and point of impact extrapolation (NASS/CDS Case ID: 2009-43-10).

Previous studies have indicated that detection and correction errors could permit PMs to persist for longer than the amount of time that the EDR preserved data (typically 5 s), and PMs of these durations have been observed.[27,40] For events wherein there was no accelerator pedal application rate of at least 25%/s but the average accelerator pedal position was greater than 75% throughout the entire pre-crash period, a PM was assumed to have occurred prior to the measurements and the time of PM and the speed at the time point of PM were conservatively estimated as the first recorded measurements.

The vehicle speed was integrated by way of a trapezoidal Riemann sum from the point of impact to the point of PM to calculate the approximate distance to impact along the path of the vehicle. The time-to-collision (TTC) was defined as the ratio of that distance to the vehicle speed and was calculated at the point of PM for each case.

Further EDR analysis investigated pedal behaviors such as simultaneous application of the accelerator and the brake ("fat-footing") and a full application of the accelerator pedal ("pedal flooring," defined as an accelerator pedal application of 99% or greater). The frequencies of both of these behaviors among the PM crashes were calculated. The frequency of changes to the configuration of the engaged pedals, ("pedal switching") was also analyzed. If the configuration of the engaged pedals changed from one measurement to the next (e.g., from only accelerator engagement to fat-footing), a pedal switch was recorded. The quantity of pedal switches per crash was normalized with the pre-crash time period to calculate the pedal switch rate, i.e., the number of pedal switches the driver performed per second during the pre-crash time period.

4.3.3 Crash Characterization

For comparison with the analyses of NMVCCS and the NC state crash database described in the previous chapter, the identified crashes from NASS/CDS were analyzed according to factors hypothesized to associate with PM. The distributions of the factor levels were plotted using the NASS/CDS sampling weights and then compared to the distribution among all case weights from NASS/CDS (regardless of EDR data availability) to identify population differences. The factors analyzed in this report are listed below in Table 5.

Table 5. List of factors analyzed among identified NASS/CDS cases.

Table	Variable	Description
Accident	ALCINV	Alcohol Involved
Accident	DRGINV	Drugs Involved
Accident	TIME	Crash Time
Accident	DAYWEEK	Crash Weekday
GV	TRAVELSP	Police-Reported Travel Speed
GV	WEATHER/CLIMATE	Weather
GV	SPLIMIT	Posted Speed Limit
GV	BODYTYPE	Vehicle Body Type
GV	DRIVDIST	Driver Distracted
GV	FATIGUE	Driver Fatigue
OA	AGE	Age
OA	SEX	Sex
OA	HEIGHT	Height
OA	INJSEV	Injury Severity

4.4 Results

4.4.1 Frequency

In total, the database contained 14,605 events associated with EDR modules from vehicles involved in NASS/CDS crashes. After filtering for accelerator pedal position and vehicle speed data availability and for events occurring during the latest ignition cycle with either a delta-v of at least 8 kph or airbag deployment, the sample was reduced to 1,525 events. The PM-specific filters were applied to this sample and identified 77 crashes that contained evidence of PM (Table 6). Because there existed no data in NASS/CDS to validate the intention of the driver during the pre-crash period, these crashes could not be confirmed as PMs. They are hereby referred to as PM-like crashes. These PM-like crashes represented 5.0% of the eligible cases and 4.3% of the eligible cases' sample weights.

Table 6. Numbers of cases and weighted cases from the population of eligible cases established in Table 3 that satisfied the PM filters. The last row indicates how many cases and weighted cases satisfy all filters, and, therefore, represents the sample of PM-like crashes identified.

PM Filters	Cases	Weighted Cases
Eligible Population	1,525	770,628
Accelerator Pedal Application Filter	343	152,582
Crash Type Filter	113	50,543
Full Stop Filter	109	49,383
Intersection/Interchange Filter	77	32,882
PM-Like Crashes	**77**	**32,882**

4.4.2 Event Data Findings

A cumulative distribution function of vehicle speed at the point of PM for each identified crash was plotted and is illustrated in Figure 36. The median vehicle speed at the point of PM was slightly greater than 75 kph (46.6 mph).

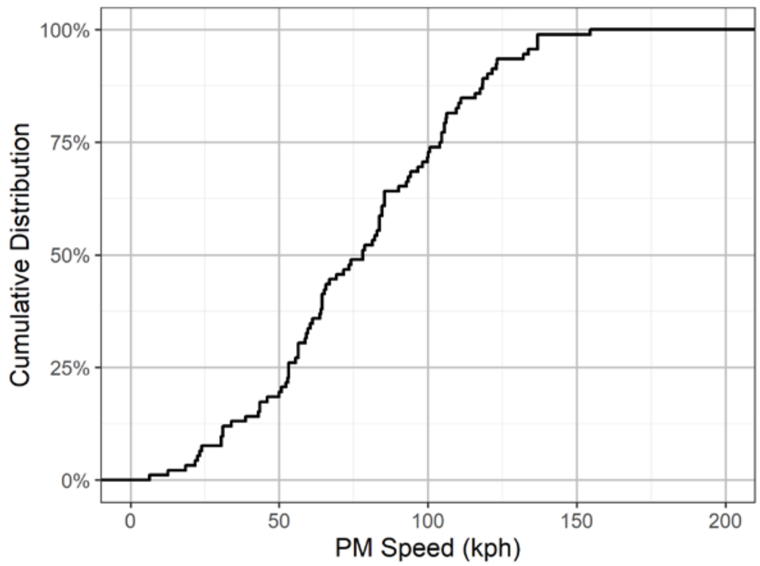

Figure 36. Cumulative distribution function of vehicle speed at the point of PM.

A scatterplot of the vehicle speed against the distance to the collision at the time-point of PM for each crash is displayed in Figure 37. As TTC was defined to be the ratio of the distance to the speed, it appears on Figure 37 as the slope of a line connecting each point to the origin. The average TTC for these crashes at the moment of PM was 2.24 s.

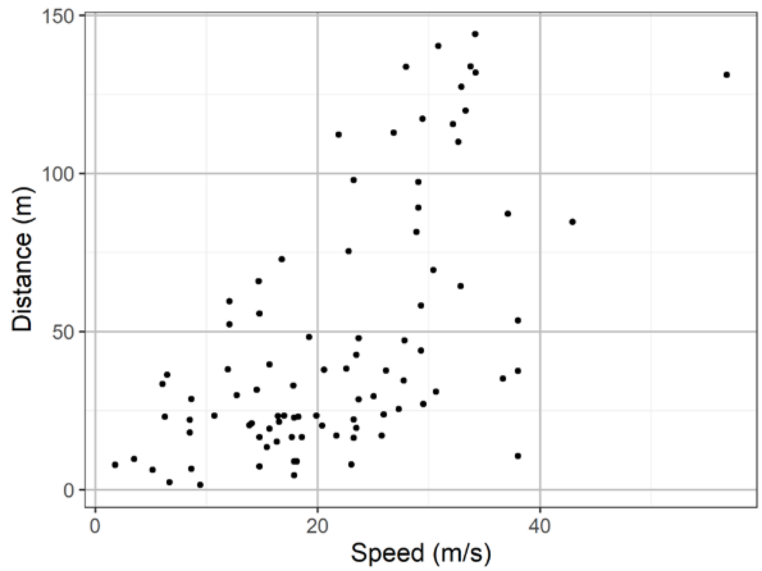

Figure 37. Scatterplot of the distance to the collision (m) against vehicle speed (m/s) at the time-point of PM for each PM crash.

A cumulative distribution function was plotted according to TTC at the moment of PM, and it was observed that over half of PM-like crashes an associated TTC of less than two seconds (Figure 38).

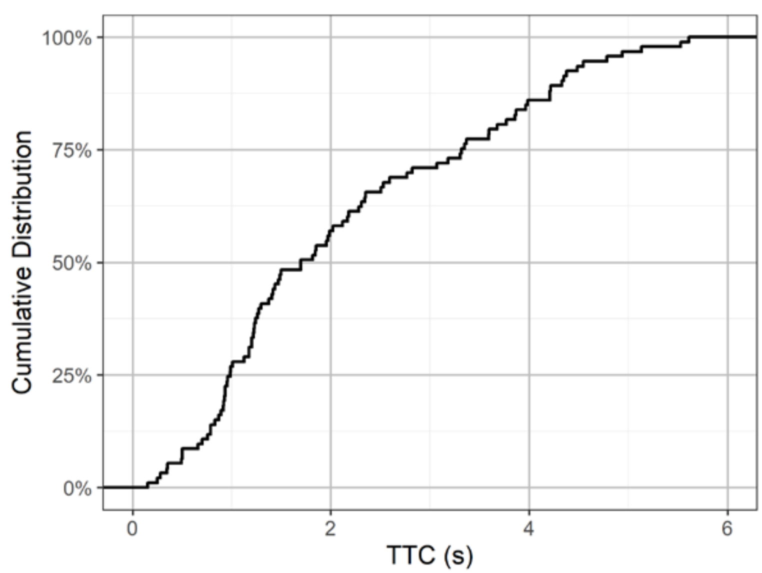

Figure 38. Cumulative distribution function of TTC for PM-like crashes.

The maximum accelerator pedal application rate, defined as the maximum ratio of the difference in measured accelerator pedal position between two adjacent measurements to the sampling period, was also investigated and compared to the population of all crashes with accelerator pedal position data available (Figure 39). As expected given the identification filters, the maximum stroke rate of PM-like crashes was substantially higher than that of all crashes. The median maximum accelerator pedal application rate of all crashes was close to 0%/s, whereas for PM-like crashes was approximately 70%/s.

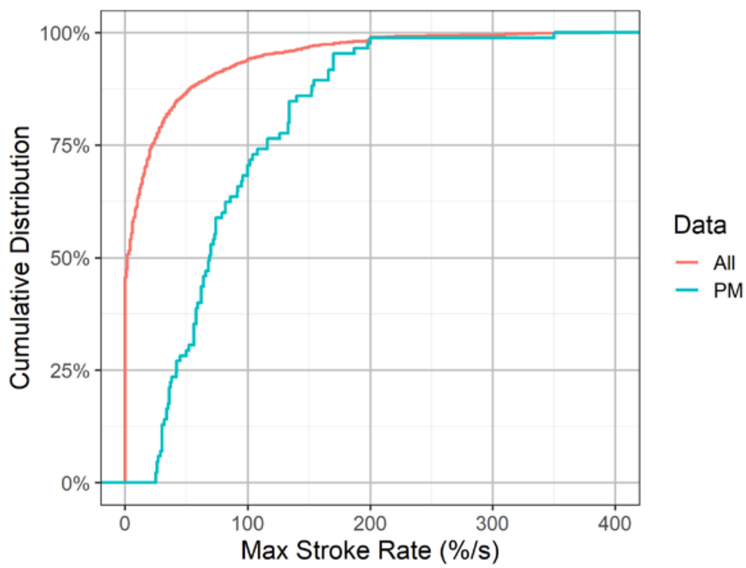

Figure 39. Cumulative distribution functions of maximum accelerator pedal application rate for all crashes and PM-like crashes. Some maximum stroke rates were greater than 100%/s because some sampling periods were less than one second.

Within the sample of 77 PM-like crashes, 27 crashes (8,962 weighted cases) involved the driver flooring the accelerator pedal during the measured pre-crash period. This corresponded to 27.3% of the sample's weighted cases. Additionally, among the 71 PM-like crashes for which braking status data was available, 11 cases (3,343 weighted cases) involved the driver fat-footing both the accelerator and the brake pedals simultaneously at some point during the measured pre-crash period, corresponding to 11.4% of that sample's weighted cases. Figure 40 shows an exemplar PM-like crash in which the driver floored the accelerator and fat-footed the accelerator and the brake. The vehicle was braking with no accelerator pedal engagement for one second, followed by 1.5 seconds of no braking and full engagement of the accelerator pedal. The accelerator pedal was then released for a moment and the brake pedal is engaged, followed by simultaneous engagement of the accelerator and the brake pedals during the final half second before impact.

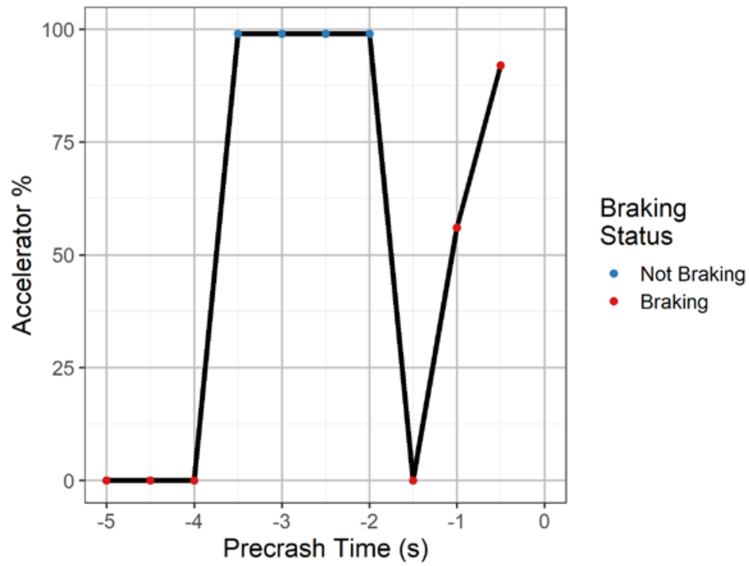

Figure 40. Example of the time-series accelerator pedal application (%) during the five-second pre-crash sequence of a PM-like crash (NASS/CDS Case ID: 2014-73-117).

Within less than five seconds, this driver changed their pedal engagement configuration three times: 1) from brake to accelerator at 3.5 s pre-crash, 2) from accelerator to brake at 1.5 s pre-crash, and 3) from brake to accelerator and brake at 1.0 s pre-crash, corresponding to a switch rate of approximately 0.7 switches per second. After analyzing pedal switch behavior of all PM-like drivers of vehicles that had EDRs with brake status data, the average number of pedal switches was 2.0, and the average switch rate was 0.6 switches per second. The cumulative distribution of pedal switches for all PM-like crashes that had available brake status data is shown in Figure 41.

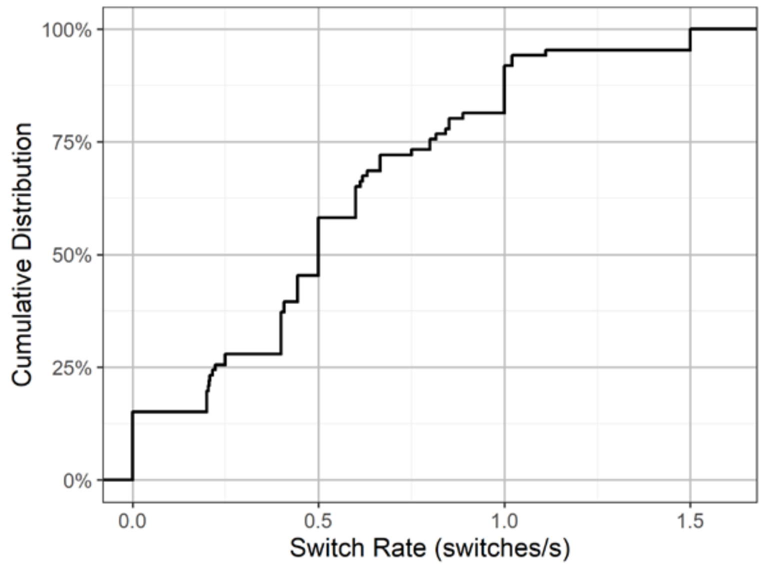

Figure 41. Cumulative distribution function of pedal switch rate among the 71 PM-like crashes with available brake status data.

Pedal switch rate was also investigated with respect to driver age in Figure 42. Drivers older than 65 years generally had a lower pedal switch rate compared to younger and middle-aged drivers; however, the older age group contained the smallest sample size (n = 8). This result is commensurate with previous research concluding that older drivers have slower reaction times and pedal switch times.[39,42,45,106]

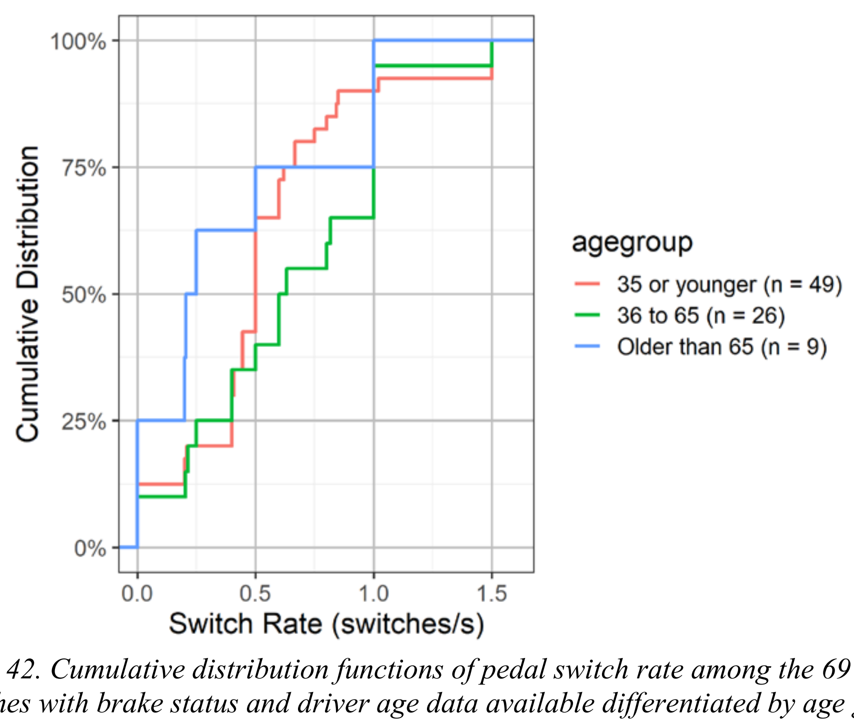

Figure 42. Cumulative distribution functions of pedal switch rate among the 69 PM-like crashes with brake status and driver age data available differentiated by age group.

4.4.3 Crash Characteristics

These aforementioned factors were investigated among the 77 PM crashes with a sum case weight of 32,882 and compared to the 82,755 total crashes with a sum case weight of 43,623,355. Sample sizes for each particular factor after unknown values were excluded are organized in Table 19, included in the appendix.

The alcohol involvement variable recorded whether the responding law enforcement officer opined that alcohol was or was not involved in each crash. As seen in Figure 43, there was no substantial difference in the proportion of crashes with alcohol involvement for PM crashes in comparison to all crashes.

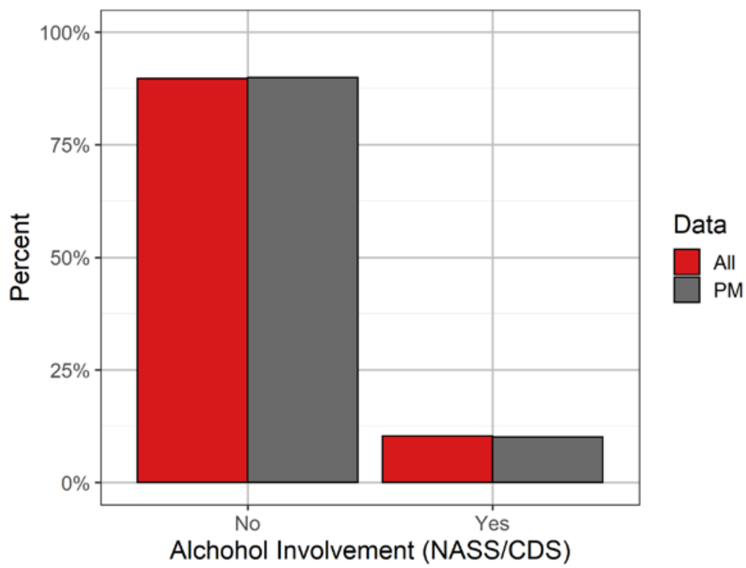

Figure 43. Distribution of alcohol involvement among all crashes and PM-like crashes in NASS/CDS.

The following factor recorded whether drugs were or were not involved in each crash. Figure 44 illustrates that there was no substantial difference in the proportion of crashes with drug involvement for PM-like crashes in comparison to all crashes.

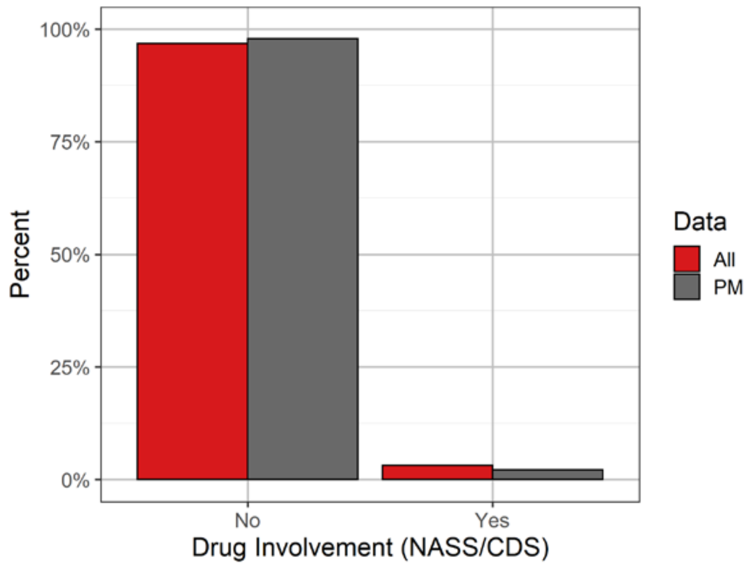

Figure 44. Distribution of drug involvement among all crashes and PM-like crashes in NASS/CDS.

In terms of crash time, the largest proportion of PM-like crashes occurred during the hours of 12:00, 15:00, and 18:00. Additionally, Figure 45 shows there were noticeably more PM-like crashes that occurred during the hours of 03:00, 05:00, 12:00, and 24:00 in comparison to all crashes during that respective hour.

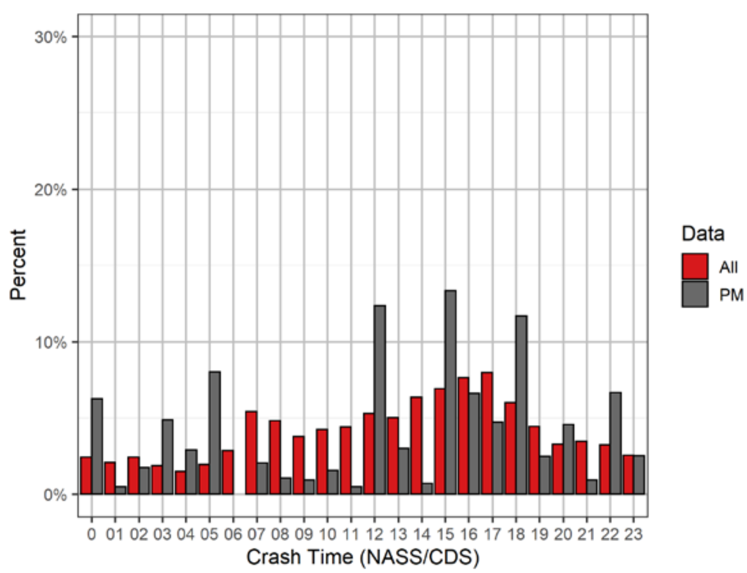

Figure 45. Distribution of crash time (hour) among all crashes and PM-like crashes in NASS/CDS.

The crash weekday distribution is illustrated in Figure 46 and shows that the proportion of PM-like crashes that occurred on Saturdays was approximately 16% higher than that of all crashes. However, the proportion of PM-like crashes that occurred on Sundays was about 9% less than all crashes. There were also increased proportions of PM-like crashes as compared to all crashes on Wednesday, Thursday, and Saturday, but decreased proportions on Monday, Tuesday, Friday, and Sunday.

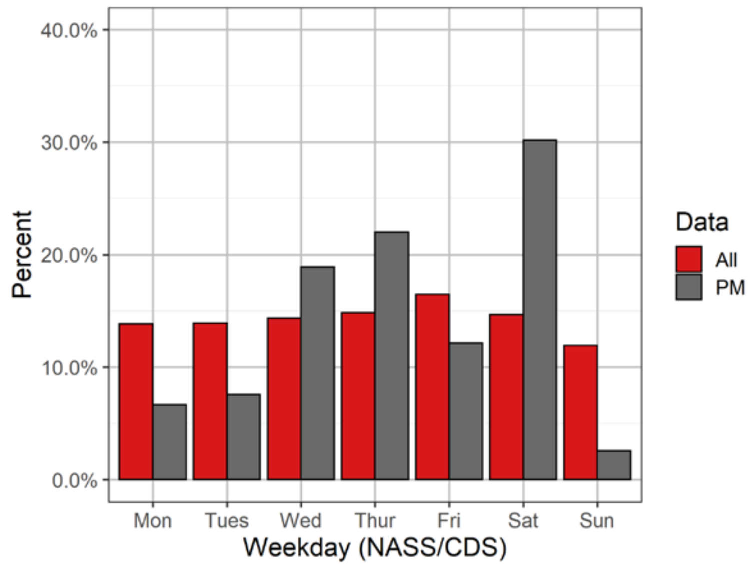

Figure 46. Distribution of crash weekday among all crashes and PM-like crashes in NASS/CDS.

Figure 47 illustrates that the police-reported travel speed at impact in all crashes trended lower than that of PM-like crashes. When "Unknown" travel speed cases were removed, only 28 of the 77 cases remained included. Over 15% of PM-like crashes occurred with an estimated speed of 61-70 mph at impact in comparison to approximately 5% for all crashes.

To supplement the NASS/CDS travel speed variable, which often went unreported, the last reported vehicle speed from the EDR for each PM-like crash was tabulated and plotted in place of the police-reported travel speed. This was compared to the police-reported travel speeds of all crashes in Figure 48. The differences between the figures can be explained by different sample sizes and by the comparably large error of police-estimated travel speeds versus EDR vehicle speeds.

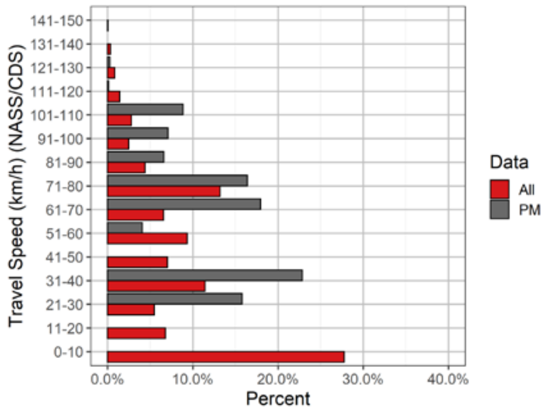

Figure 47. Distribution of police-reported travel speed among all crashes and PM-like crashes in NASS/CDS.

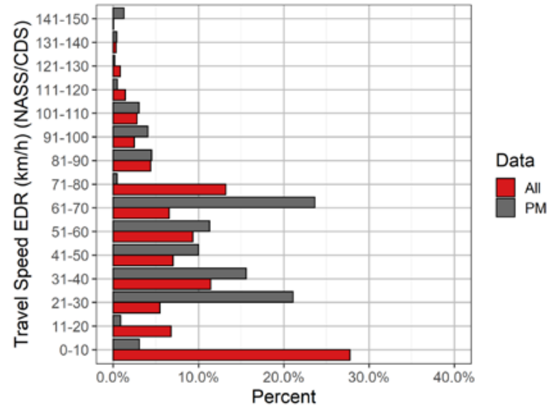

Figure 48. Distribution of EDR-reported travel speed among all crashes and PM-like crashes in NASS/CDS.

The distribution of weather factors in Figure 49 shows no substantial difference between the proportion of all crashes and PM-like crashes that occurred during any given weather factor. A slightly higher proportion of PM-like crashes occurred during clear/cloudy conditions, but the difference between all crashes and PM-like crashes is very small.

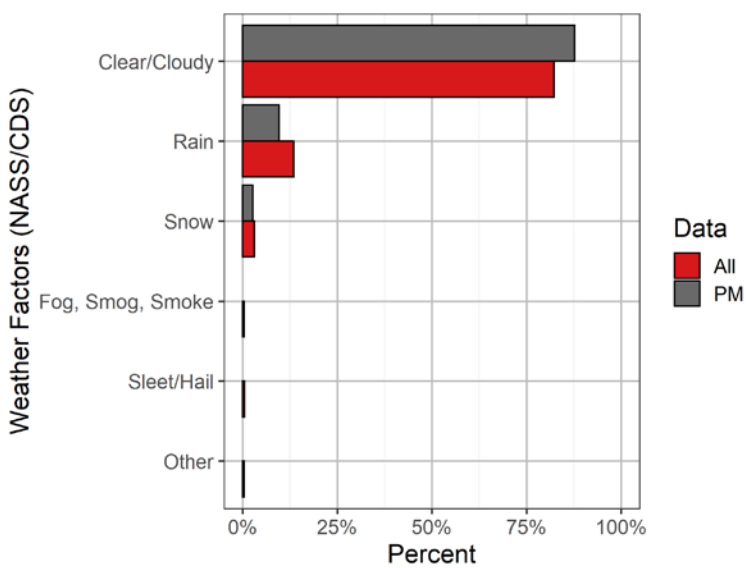

Figure 49. Distribution of weather factors among all crashes and PM-like crashes in NASS/CDS.

The highest proportion of both PM-like crashes and all crashes occurred at a speed limit of 31-40 mph, seen in Figure 50. Nevertheless, the proportion of PM-like crashes that occurred in locations with a speed limit between 51-60 mph was approximately 7% higher than all crashes. Overall, the differences between the distributions of all crashes and PM-like crashes were unsubstantial.

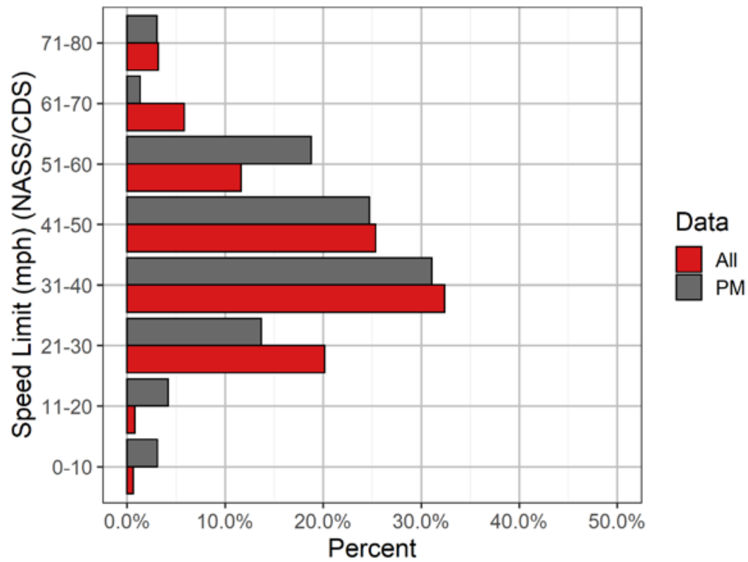

Figure 50. Distribution of speed limit among all crashes and PM-like crashes in NASS/CDS.

Figure 51 illustrates the distribution of vehicle type and shows that the majority of vehicles in PM-like crashes and all crashes were cars. However, slightly higher proportions of vehicles were cars in PM-like crashes in comparison to all crashes. This distribution is shifted toward passenger vehicles because of NASS/CDS crash inclusion criteria.

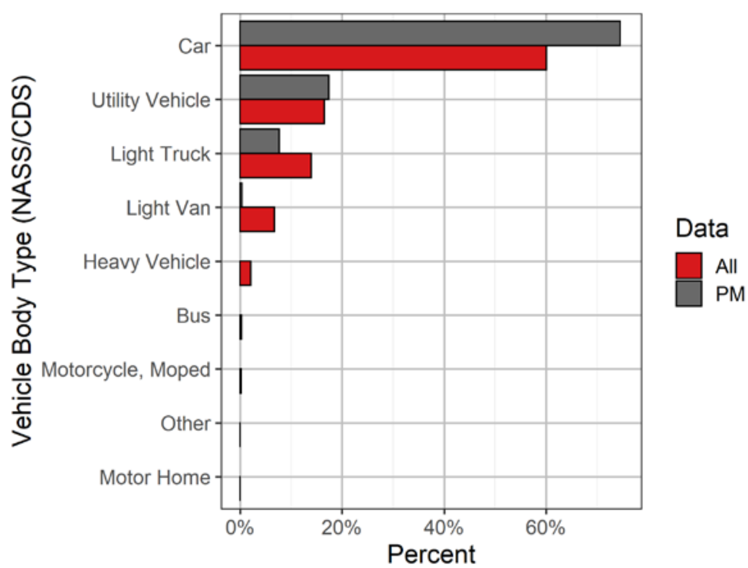

Figure 51. Distribution of vehicle type among all crashes and PM-like crashes in NASS/CDS.

There is a drastic difference in the distribution of driver distraction/inattention among drivers in PM-like crashes versus all crashes, shown in Figure 52. Over 50% of PM-like crashes occurred when there was a distraction/inattentive factor present in comparison to approximately 27% of all crashes. However, only 37 out of 77 PM-like crash cases remained in the sample once cases with "Unknown" distraction/inattention values were removed. Notably, distraction and inattention are self-reported and subject to potential underreporting, as well as differences in reporting among drivers in all crashes and drivers in PM-like crashes.

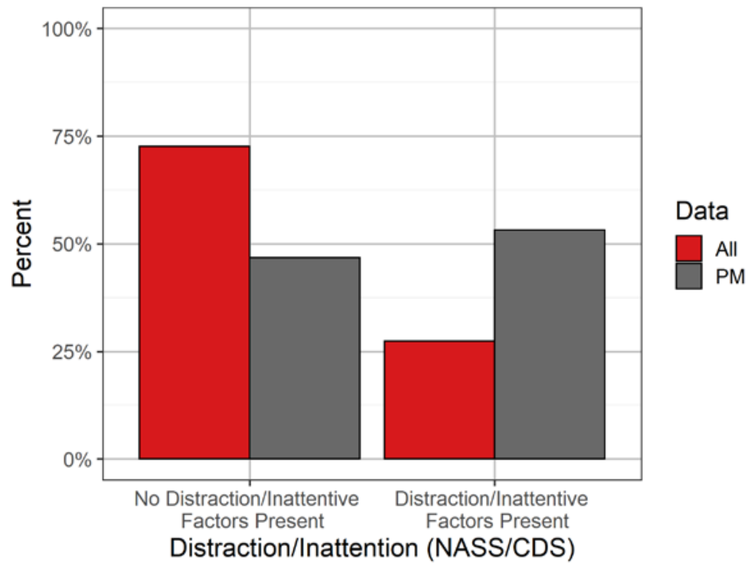

Figure 52. Distribution of driver distraction/inattention among all crashes and PM-like crashes in NASS/CDS.

Figure 53 shows that there is a noticeable difference in the proportion of fatigued drivers in PM-like crashes versus all crashes. The proportion of PM-like crashes where the driver was fatigued was approximately 9% higher than that of all crashes. Like the previous variable, it is important to note that only 37 out of 77 PM-like crash cases remained included in the sample once “Unknown” fatigue cases were removed.

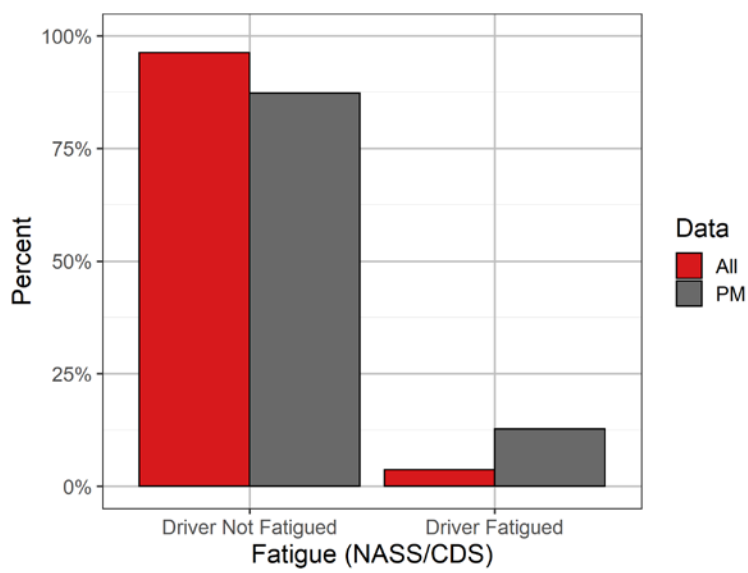

Figure 53. Distribution of driver fatigue among all crashes and PM-like crashes in NASS/CDS.

The distribution of driver age among drivers in Figure 54 illustrates that PM-like crashes occurred at a noticeably higher proportion when the driver was in the 15-34 (approximately

4.75% higher) age group or the 85-94 (approximately 7% higher) age groups in comparison to drivers in all crashes.

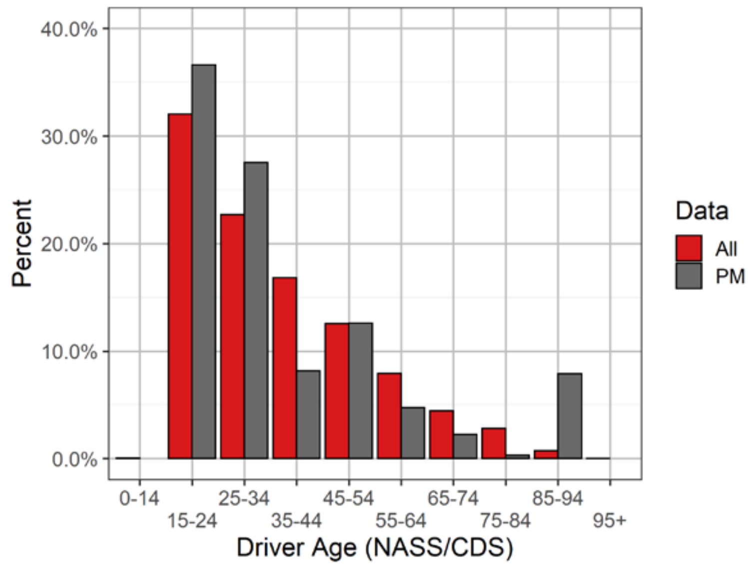

Figure 54. Distribution of driver age among all crashes and PM-like crashes in NASS/CDS.

As illustrated in Figure 55, the majority of drivers who were in all crashes or likely committed a PM resulting in a crash were male. 60.2% of drivers who likely committed a PM resulting in a crash were male, while only 55.7% of drivers in all crashes were male.

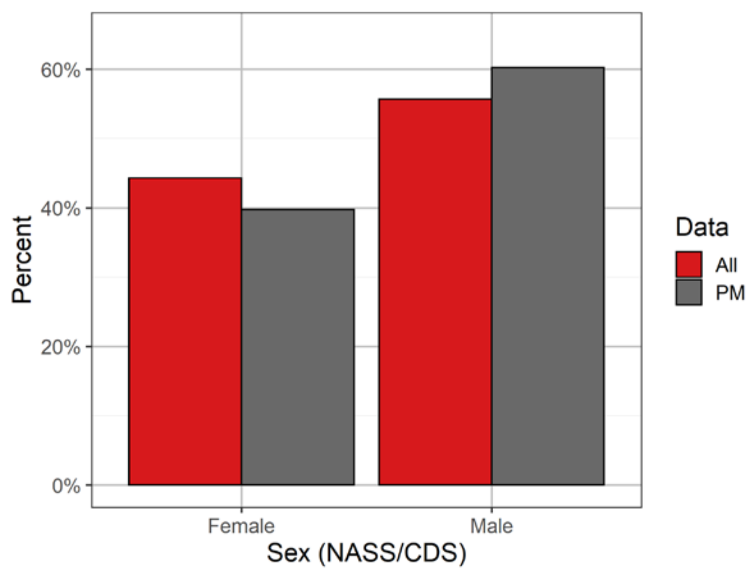

Figure 55. Distribution of driver sex among all crashes and PM-like crashes in NASS/CDS.

The distribution of driver height, shown in Figure 56, appeared to trend toward slightly taller drivers in PM-like crashes as compared to drivers in all crashes, although both median heights fall in the 170-179 cm height group. Overall, the differences between the distributions of all crashes and PM-like crashes were unsubstantial.

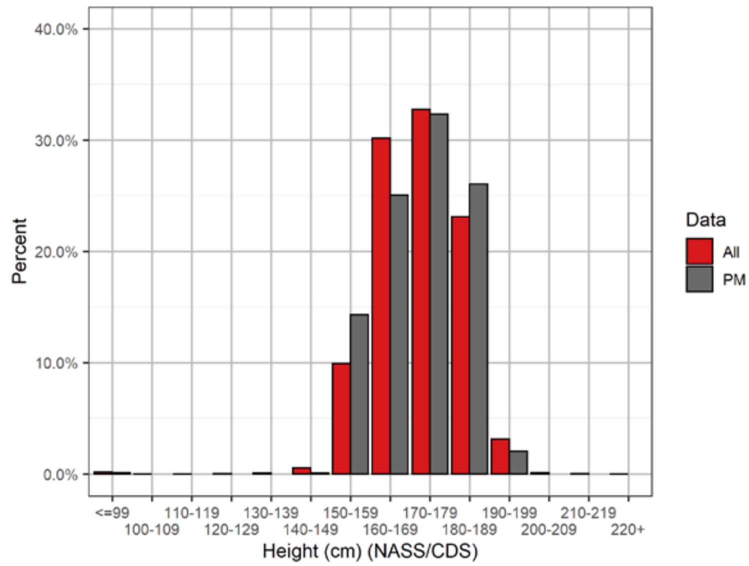

Figure 56. Distribution of driver height among all crashes and PM-like crashes in NASS/CDS.

For each crash, the maximum KABCO injury severity from all of the occupants involved was taken. Figure 57 shows that the proportion of PM-like crashes that resulted in a maximum KABCO injury severity of "No Injury" was 20.0% lower than that of all crashes and that the proportion of PM-like crashes that resulted in a maximum KABCO injury severity of "Non-capacitating Injury" was approximately 19.6% higher than that of all crashes. The proportion of PM-like crashes that resulted in a maximum KABCO injury severity of a fatality was only slightly higher than all crashes.

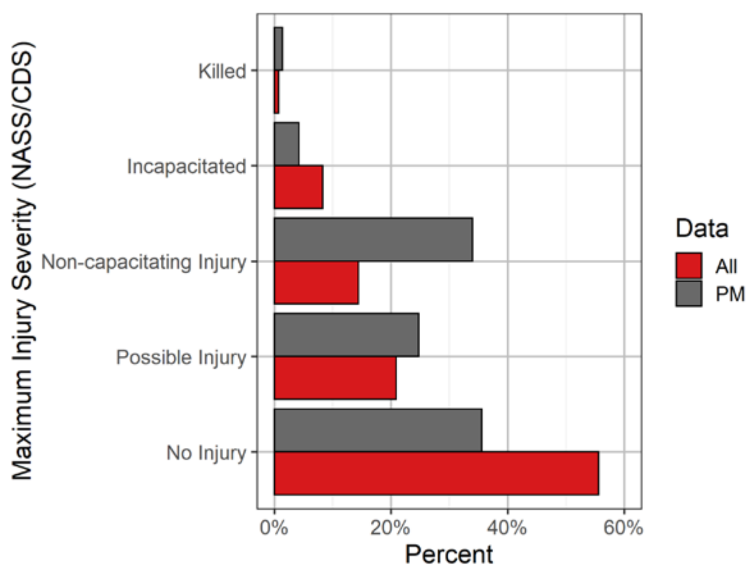

Figure 57. Distribution of maximum injury severity among all crashes and PM-like crashes in NASS/CDS.

4.5 Discussion

PM literature as well as the previous chapter have estimated the frequency of PM crashes as at least 0.2% of all crashes.[40,41,49] While the methodological limitations of the keyword search suggested that the true frequency was higher, there have been no estimates as to how high it could be. The rate of crashes that exhibit pre-crash event data evidence of PM as determined in this study suggest that the true frequency of PM may be an order of magnitude higher than previously estimated.

The TTC analysis of PM-like crashes revealed that, at the time of PM, most vehicles had at least 2 s before impact assuming they maintained their speed. Without any driver assistance intervention, this is clearly an inappropriate assumption, because an increase in speed typically follows a PM; however, this calculation provides utility for the consideration of an ADAS designed to suppress PM acceleration pedal input. It is a promising result because previous research has observed safety benefits with substantially shorter TTCs. For example, Kusano and Gabler modeled the safety benefits of a pre-crash braking system in rear-end crashes using a TTC of less than half-a-second and observed a significant reduction in crash severity.[14] In the sample of PM-like crashes, more than 90% had a TTC greater than Kusano and Gabler's threshold, suggesting that a significant portion of PM crashes may be subject to such a crash severity reduction if an effective countermeasure was developed.

Investigation of pedal flooring behavior concludes that more than one in four drivers represented in this set of PM-like crashes engaged the accelerator to over 99%. These represent an important subset of PM crashes because they are such extreme misapplications. While it cannot be determined from this data whether full engagement of the accelerator prior to the crash was done in error as opposed to intentional acceleration, e.g., accelerating as an evasive maneuver, it can be confidently stated that simultaneous application of both the brake and the accelerator is the result of a mistake. In other words, even though the identified sample of crashes was characterized at large as PM-like crashes, crashes that involved fat-footing could be confirmed as PM crashes. This behavior was observed in 11.4% of the PM-like crash weights that had available brake status data. Of all of the eligible crashes, it was observed in 0.4% of crash weights. This result suggests that PM crashes are at least twice as frequent as previous studies have estimated using the keyword search method. Yet, because fat-footing PM crashes are a subset of all PM crashes, the true frequency of PM crashes is greater still. Further, there was extensive pedal switching behavior during the moments leading up to these crashes. With more pedal switches, the odds of misapplying a pedal could increase because the driver is exposed to more opportunities to place their foot in the wrong place. Conversely, after a PM, it is expected that a driver would react by correcting their misapplication if they have time, thereby increasing the number of switches. Both of these are possible justifications for the observed average pedal switch rate of 0.57 switches per second pre-crash among likely PM with available brake data.

In terms of the crash characteristics recorded by the NASS/CDS crash investigators, the involvement of alcohol or drugs in the crash did not appear to have any substantial effect on the proportion of PM-like crashes in comparison to all crashes. The results of the analysis of both factors echoed the results of the analyses of PM crashes in NMVCCS and the NC state crash database.

The highest proportions of PM-like crashes occurred between the hours of 12:00, 15:00, and 18:00. The majority of the hours with the greatest increase in PM-like crashes in comparison to all crashes were all during the early morning or late at night, as seen in the NMVCCS data as well. The drivers suspected of committing a PM in PM-like crashes were much more likely to be distracted/inattentive or fatigued in comparison to drivers in all crashes. The fatigue result suggests a possible relationship between the increased prevalence of early morning and late-night crashes among PM-like crashes. This trend is seen in NMVCCS data as well; however, the proportion of PM-like drivers who are distracted/inattentive is noticeable higher in the NASS/CDS data. It is important to note that unlike NASS/CDS, NMVCCS had a trained investigator on the scene of the crash who can interview the driver. Further, the proportion of PM-like crashes observed in NASS/CDS that occurred on Saturdays was much higher than that of all crashes unlike the NC state crash database analysis, where there appeared to be no substantial difference in the proportion of PM crashes versus all crashes on a given day of the week.

From this sample, PM-like crashes appear more likely to occur at higher travel speeds than that of all crashes, but not necessarily in locations with substantially higher posted speed limits. This result contradicts those observed in NMVCCS and the NC state crash database. Anecdotally, a high prevalence of PM crashes identified from the narratives of NMVCCS and the NC state crash database occurred at intersections. In this study's method, crashes that occurred at intersections were not included in the PM-like crash sample in an effort to increase the specificity of PM-like crash identification. Because intersections are more prevalent on low-speed roadways, this may explain why PM-like crashes appear to tend toward higher travel speeds.

Weather did not appear to be a contributing factor to PM-like crashes as there was no considerable difference in proportion of PM-like crashes as compared to all crashes. This agreed with the trends observed in the NMVCCS and NC state crash data.

In this study, drivers involved in PM-like crashes were more likely in the age range of 25-34 or 85-94 years old as compared to drivers in all crashes. They were also more likely to be male, which is an inversion of the consistent result found throughout the past decades of PM research. In NMVCCS and NC state crash database, drivers involved in PM crashes were characterized as more likely to be female and shorter. Sex likely confounds with height, as males are taller than females on average. This could explain why PM driver height relative to drivers in all crashes increased when comparing NASS/CDS to NMVCCS, as more males were observed in the former sample. The characterization of PM-like drivers as majority male in NASS/CDS is particularly interesting and could possibly be linked to the observation of higher speeds in PM-like crashes. There may be reason to believe that the gender distribution is not constant with respect to speed, and, as a result of the exclusion of low-speed intersection crashes, only a subset of PM-like crashes which tend toward male drivers were identified. It is also supported that males were less likely to admit to a PM, and, therefore, were likely consistently underrepresented in keyword search analyses that relied on admittance.[56]

Like all crashes, PM-like crashes from this sample were most likely to result in lower severity injuries. In the NMVCCS and NC state crash database analyses, the maximum police-reported injury severity of PM crashes was less likely to be fatal, incapacitating, or non-capacitating when compared to all crashes. Alternatively, in NASS/CDS, PM-like crashes were relatively more likely to result in a fatality, non-capacitating injury, or possible injury than crashes generally. This is likely associated with the methodological differences of the EDR PM identification method, which notably resulted in trends of higher speeds than those found in PM crashes identified by keyword search. In other words, EDRs can implicate PM even when deceased and incapacitated drivers cannot. Compared to the NC state crash database, NMVCCS and NASS/CDS injury severities are also influence by relatively stricter crash inclusion criteria, including tow-away vehicles.

4.5.1 Limitations

EDR data was required for this analysis, which was not common among crash databases at the time. For crashes that did have associated EDR data, the EDR data must have had pre-crash accelerator pedal position, pre-crash speed, crash delta-v or airbag deployment, and the event ignition cycle data to be included in this analysis. These EDR data requirements reduced the sample size to 1,525 crashes. The TTC calculations were subject to temporal error due to the low sampling frequency of EDRs (typically 1 Hz for pre-crash parameters). In addition to increasing the error of all time-dependent calculations based on pre-crash measurements, the low sampling frequency likely resulted in an underestimated pedal-switch rate, because the EDR may not have captured all of the changes to the pedal configuration. Additionally, because there is a specific order and timing of data elements incoming to the EDR via the controller area network from various sensors throughout the vehicle, different data elements are received at slightly different times.

The speed represented in the EDR is the speed displayed on the speedometer, which is the measured tire speed rather than the true speed of the vehicle relative to the ground. When the vehicle is tracking, the difference is negligible; however, this assumption produces error any time traction is lost, such as in skidding due to oversteer/understeer or hard braking (more prevalent in older vehicles not equipped with electronic stability control or anti-lock braking systems). The error of the TTC calculations and any other calculations derived from EDR-reported vehicle speed are limited to the extent that the vehicle was not tracking. Furthermore, NASS/CDS crash inclusion criteria required at least one vehicle to be towed from the scene. This, along with the filter for a minimum delta-v of 8 kph or airbag deployment, biases the results toward more severe crashes.

Additionally, it is almost certain that some non-PM crashes were identified as PM-like crashes, and, conversely, some PM crashes were not identified as PM-like crashes. For example, events which involved drivers who accelerated before a crash as a failed avoidance maneuver may not have been a PM crash but may have been identified as a PM-like crash. By excluding intersection crashes, the specificity of PM crash identification was improved by reducing the number of false positives, since heavy accelerator application is common around intersections; however, this excluded true positives by ignoring PM crashes that occur in or around intersections. These excluded PM crashes may represent a population that have different characteristics than those identified in this study, such as lower speeds and lower maximum injury severities, and their absence could explain some of the characteristic differences between the results of the analyses of previous databases. A similar effect is expect with the exclusion of PM crashes occurring from a full stop. In essence, the results are limited to the extent that the algorithm did not correctly identify PM crashes. Also, by limiting the identification of PM-like crashes to pre-established crash types from previous research, an investigation into the effect of the identification method on the crash type distribution of PM-like crashes was prevented.

4.6 Conclusions

This study implemented a novel alternative for PM crash identification to supplement the previous keyword searches of decades past. This method identifies crashes that exhibit evidence of PM via EDR time-series data and is not limited by subjective and inconsistent crash narratives. After analyzing a subset of NASS/CDS pre-crash EDR data, evidence of PM was observed in 4.3% of represented crashes. This result was an order of magnitude higher than previously estimated PM crash frequencies. Pedal flooring, simultaneous pedal engagement, and pedal switching were analyzed to investigate the pedal dynamics of PMs.

Further characteristics of these crashes were analyzed for comparison with all NASS/CDS crashes and previously identified samples of PM crashes from other data sources. While many of the characteristics followed similar trends as those of PM crashes in the previous databases, NASS/CDS PM crashes were observed to trend toward higher speeds, taller and male drivers, more severe injuries, and higher prevalence of distraction or inattention.

Chapter 5: Identifying Pedal Misapplication Crashes in a Naturalistic Driving Study

5.1 Introduction

The keyword search identification method functioned well to identify and analyze a subset of PM crashes for anecdotal observations from the narratives and general, pre-coded factors collected by law-enforcement officers and trained crash investigators, but failed to provide an in-depth, time-series perspective into the pre-crash behavior of PM drivers. The EDR identification method excelled where this method fell short but failed to verify many of the identified PM crashes, limiting the analysis to that of mostly PM-like crashes with a small subset of confirmed PM-crashes. PMs have been studied in driving simulators or small-scale, short-term, in-vehicle driving studies, often with on-board researchers (see Chapter 2).[22,25,35,36,44,46,91,107] Many of these studies provide a crucial perspective into driver behavior that would be challenging or unfeasible to capture with other methods. However, these methods may not capture representative driver behavior to the extent that the simulator environment, driving scenarios, or other experimental conditions influence the drivers to behave unlike they would in normal driving. Additionally, because PMs are rare events relative to all pedal applications (and PM crashes are even fewer), they are difficult to naturally replicate in these studies.

The naturalistic driving study is an innovative observational research method designed to provide the most comprehensive perspective of driving behavior to date.[108] Vehicles are instrumented with data acquisition systems, sensors, and interior and exterior cameras that continuously record and store information relating to daily driving. In many naturalistic driving studies, volunteers use their own vehicles and the equipment installed in the vehicle can be relatively inconspicuous. For long-term naturalistic driving studies, the effects of experimental design artifacts are thought to quickly diminish such that the driving observed is representative of the subject's normal driving.

5.2 Data Source

The data source for this study was the Second Strategic Highway Research Program Naturalistic Driving Study (SHRP 2 NDS) dataset of crash and near-crashes. The SHRP 2 NDS is the largest naturalistic driving study with video data to date, containing approximately three petabytes of data from over 3,300 instrumented vehicles travelling more than 32 million miles between the years of 2010 and 2013.[109] The data acquisition system recorded five video views, vehicle network data, and further data from an accelerometer, gyroscope, and GPS. A total of 30 vehicle factors, 76 event factors, 142 trip factors, and 186 time-series data factors were recorded in addition to a variety of driver questionnaires. By the end of the study, more than 1,900 crashes and nearly 7,000 near-crashes had been documented. The scale of the SHRP 2 NDS provided an opportunity to identify and observe the rare and elusive PM, and its depth allowed for a robust look at the PM crashes. Notably, this includes the ability to cross-references crashes characterized by high pre-crash accelerator pedal application rates with driver-facing video to determine the intention of the driver and verify these events as PMs.

5.3 Methods

5.3.1 Pedal Misapplication Identification

Similar to the previous chapter, this analysis leveraged the accelerator pedal application rate and vehicle speed to narrow the dataset to subset of potential PM events and conduct the analysis. Thus, events in which the accelerator pedal position or vehicle speed was not recorded were not included. Crashes were the primary focus of this study, so only crashes were included. This allowed the results to be compared to the analyses of prior crash databases (NMVCCS, the NC state crash database, NASS/CDS). Separately, a small sample of near-crashes were selected and analyzed to investigate PMs outside of the crash scenario. These results are covered separately in Chapter 5.4.3.

Based on the same principles that guided the EDR study, only crashes in which the pedal application rate reached at least 25%/s or the average accelerator pedal position was at least 75% over a five second pre-crash time period were included. Once the cases were narrowed down by these filters, the forward-facing video of each of the potential PMs were reviewed. The crashes in which the forward-facing camera view indicated that a PM may have occurred were then manually reviewed in the secure data enclave at VTTI. This enabled the researchers to review all camera angles (forward view, rear and right view, driver and left side view, passenger snapshot view, and interior cabin view positioned behind, above, and to the right of the driver facing downward at the instrument panel and steering wheel) synchronized with the time-series vehicle metrics. The videos of the event were reviewed alongside graphs of accelerator pedal position, brake status, and vehicle speed. This synchronized view of each potential PM allowed the researcher to make an informed decision on whether to confirm the crash as a PM. Observations such as driver distraction, location, feet movement, traffic conditions, researcher-determined driver intention, and driver reaction were recorded and taken into consideration when evaluating each crash. Crashes in which the driver failed to recognize a lead vehicle and inappropriately but intentionally hit the accelerator were not considered PMs. Take, for example, the following crash scenario that was observed repeatedly by researchers during manual review: A subject vehicle is stopped in a right turn lane preceding an intersection waiting for a lead vehicle to turn. The lead vehicle accelerates slightly, and so does the subject vehicle. The driver of the subject vehicle believes the lead vehicle to be committed to the turn and continues to accelerate while turning their attention to their left to check for oncoming cross traffic. Ultimately, the lead vehicle does not turn and instead brakes to a stop. As a result, the subject vehicle accelerates into it, causing a rear-end crash. Depending on the accelerator pedal application rate of the subject vehicle, this crash could be captured as a potential PM crash; however, this crash would be excluded upon review of the driver-facing video because the driver intended to hit the accelerator but, due to their distraction, did not realize the lead vehicle was in their path. In any case, if the researcher determined that the driver's acceleration was intentional, then it was not considered a PM. The number of crashes that passed through each subsequent filter is tabulated in Table 7.

Table 7. Numbers of crashes that satisfied the PM filters. The last row indicates how many crashes satisfied all filters, and, therefore, represents the sample of confirmed PM crashes identified

PM Filters	Crashes
SHRP 2 NDS Crashes	1,836
Pre-crash Accelerator Pedal Position Data Available	1,400
Pre-crash Vehicle Speed Data Available	1,143
Acceleration Pedal Application Threshold Met	431
Suspected PM from Forward-facing Video	33
Confirmed PM Crashes	**13**

5.3.2 Time-Series Data Analysis

For the time-series data analysis, the moment of PM was defined to occur at half the sampling period before the first increase in accelerator pedal position of at least 25%/s. A noteworthy difference between the time-series data in this analysis and the EDR analysis is that the sampling frequency of the SHRP 2 NDS vehicle measurements was 10 Hz versus a typical frequency of 1-2 Hz in the EDRs included in NASS/CDS. So, for example, if accelerator position increased from 0% at 1.5 seconds pre-crash to 10% at 1.4 s pre-crash with a sampling frequency of 10 Hz, the time of PM was estimated to occur at 1.45 s pre-crash. This minimizes the temporal error in the PM time because the pedal was applied at an unknown time between those two samples. The vehicle speed at the time of PM was linearly interpolated from the bordering speed measurements immediately before and after the time of PM.

Additionally, the impact proximity was measured at an approximately 15 Hz frequency, which did not align with the 10 Hz sampling frequency of the accelerator pedal position and vehicle speed. Therefore, for the time-series data analysis, the time of impact for each crash was rounded down to the previous tenth of a second. In other words, the time of impact was taken as the last timestamp prior to the impact proximity point. Accordingly, accelerator pedal position, braking status, and vehicle speed at impact were defined as the values at the last timestamp before impact.

The speed was integrated by way of a trapezoidal Riemann sum from the point of impact to the point of PM to calculate the distance travelled along the path of the vehicle. The TTC at PM was defined as the ratio of the calculated distance travelled to the interpolated vehicle speed at the point of PM. The TTC at PM was computed for each crash.

Further, the pedal dynamics were investigated to investigate noteworthy pedal behaviors. As defined in the previous chapter, these included fat-footing, pedal flooring, and pedal switching. The prevalence of these behaviors among the PM crashes were calculated. The number of pedal switches per crash was normalized with the pre-crash time period to calculate the pedal switch rate, i.e., the number of pedal switches the driver performed per second over the five second pre-crash time period.

5.3.3 Crash Characterization

Akin to PM crash characterizations of the previous two chapters, PM crashes were analyzed according to factors hypothesized to associate with PM (Table 8). The distributions of the factors were compared between PM crashes and all crashes in SHRP 2 NDS.

Table 8. List of factors analyzed in the factor analysis.

Table	Variable	Description
Event	driverImpairments	Alcohol Involved
Event	driverImpairments	Drugs Involved
Time-series	vtti.speed_network	Network Travel Speed
Event	weather	Weather
Event	locality	Locality
Vehicle	classification	Vehicle Classification
Event	secondaryTask1	Driver Distracted
Event	driverImpairments	Driver Fatigue
Driver Demographics Questionnaire	ageGroup	Age Group
Driver Demographics Questionnaire	sex	Gender

5.3.4 Evaluating the Performance of Event Data Recorder-Based Pedal Misapplication Crash Identification

The set of confirmed PM crashes from SHRP 2 NDS was used to evaluate the performance of the NASS/CDS EDR PM identification algorithm described in Chapter 4. This algorithm included a set of data filters that isolated PM-like crashes. These filters excluded crashes accelerating from a full stop (crashes where a vehicle was travelling at a speed of less than 1 kph at any point in the five second pre-crash period), excluded all crashes which occurred in or around intersections and interchanges, and excluded all crash types other than road departure, end departure, rear end, forward impact, and backing crashes. Lastly, only crashes in which the accelerator pedal application rate reached at least 25%/s or the average pedal application was at least 75% over the five second pre-crash time period were included. This algorithm was applied to the SHRP 2 NDS dataset of crashes, and the identified PM-like crashes were compared to the PM crashes confirmed by manual inspection. The precision, recall, accuracy, and F1 scores of the EDR algorithm and its individual filters were calculated. Additionally, each criterion (full stop, crash type, intersection) was evaluated to investigate its effect on the precision, accuracy, or F1 score of the algorithm as a whole.

Precision is the probability that a PM-like crash was confirmed as a PM crash, calculated as the number of true positives divided by the sum of the true and false positives (Equation 1). In this case, precision was the ratio of confirmed PM crashes identified by the EDR algorithm to all PM-like crashes identified by the EDR algorithm.

$$Precision = \frac{True\ Positive}{True\ Positive + False\ Positive} \quad (1)$$

Accuracy was calculated as the sum of true positives and negatives divided by the sum of true and false negatives and positives (Equation 2). In this case, accuracy was the sum of confirmed PM crashes identified by the EDR algorithm and crashes that were correctly not identified by the EDR algorithm divided by the total sample.

$$Accuracy = \frac{True\ Positive + True\ Negative}{True\ Positive + True\ Negative + False\ Positive + False\ Negative} \quad (2)$$

Recall is the ability for the EDR algorithm to correctly identify confirmed PM crashes, calculated as the number of true positives divided by the sum of true positives and false negatives (Equation 3). In this case, recall was the number of confirmed PM crashes identified by the EDR algorithm divided by the total number of confirmed PM crashes.

$$Recall = \frac{True\ Positive}{True\ Positive + False\ Negative} \quad (3)$$

The F1 score is the harmonic mean of precision and recall. In other words, F1 score was defined as two times the product of precision and recall divided by the sum of precision and recall (Equation 4). The F1 score was used as the primary metric because it was indicative of the model's ability to accurately predict outcomes and is particularly reliable for unbalanced datasets. A higher F1 score suggests a better predictive capability of the model.

$$F1\ Score = \frac{2 * Precision * Recall}{Precision + Recall} \quad (4)$$

5.4 Results

5.4.1 Frequency

In total, the SHRP 2 NDS contained 1,836 crashes. After filtering for accelerator pedal position and vehicle speed data availability, the sample was reduced to 1,143 crashes. The acceleration pedal application rate filter was applied to this sample and 431 potential PM crashes were identified. Next, each of the 431 crashes were manually reviewed by inspecting crash video, during which 13 crashes were confirmed as PM crashes. These confirmed PM crashes represent 1.1% of the crashes in the eligible population.

5.4.2 Time-Series Findings

The cumulative distribution of vehicle speed at the time of PM for all confirmed PM crashes is shown in Figure 58. The median vehicle speed at the time of PM was 5.7 kph (3.5 mph). Overall, the speed at PM is very low. The maximum speed at PM among the 13 confirmed cases was less than 11 kph (6.8 mph).

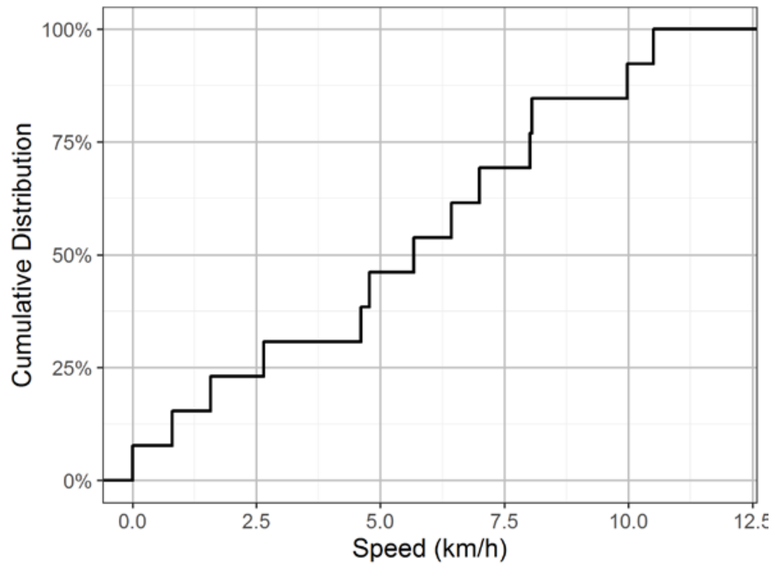

Figure 58. Cumulative distribution function of vehicle speed at the point of PM in each confirmed PM crash.

A scatterplot of the vehicle speed against the distance to the impact at the point of PM for each confirmed PM crash is displayed in Figure 59. Because TTC was defined to be the ratio of the distance to the speed, the TTC is the slope of the line connecting each point to the origin. The average TTC for these crashes at the moment of PM was 3.6 seconds. There was one crash in which the PM occurred at rest.

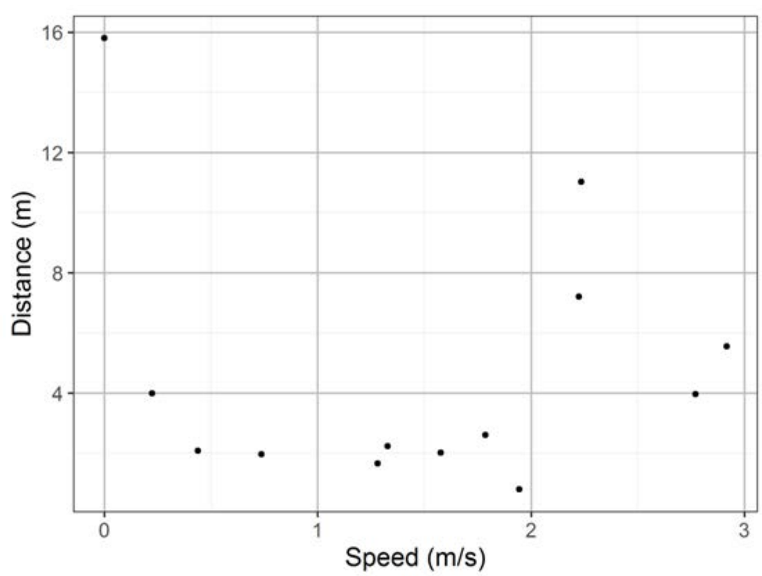

Figure 59. Scatterplot of the distance to impact against the vehicle speed at the point of PM for each confirmed PM crash.

In Figure 60, a cumulative distribution function was plotted according to TTC at the time of PM, and it was observed that approximately half of PM crashes in the sample had an associated TTC of less than 2 seconds. There was one crash which had a TTC of greater than 15 s and another which had a nonfinite TTC because the vehicle was stopped. The latter crash was excluded from Figure 60.

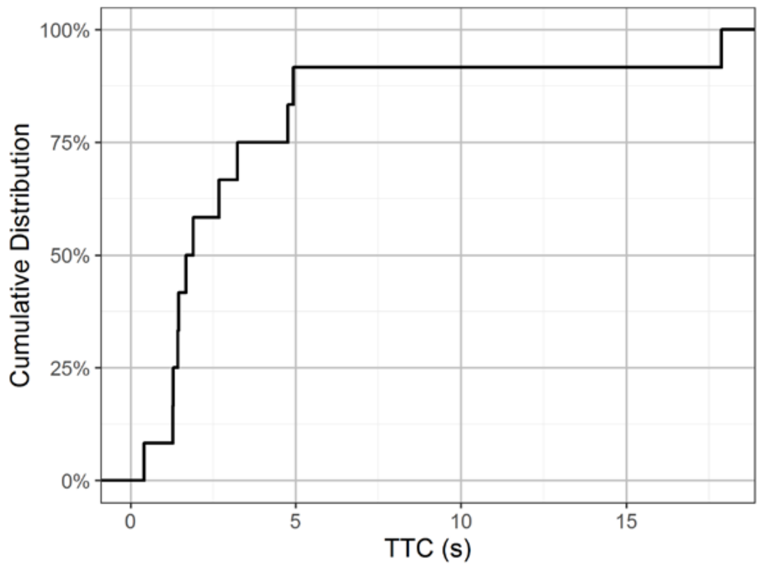

Figure 60. Cumulative distribution function of TTC at the time of PM in confirmed PM crashes.

Of the 11 crashes with available brake status data, there were three crashes in which the driver never applied the brake after committing the PM. These crashes were not included in the following TTC analysis. For the remaining eight crashes, a cumulative distribution function of TTC at brake application post-PM was plotted in Figure 61. It was observed that over 60% of PM drivers in the sample braked with a TTC of less than 0.25 seconds.

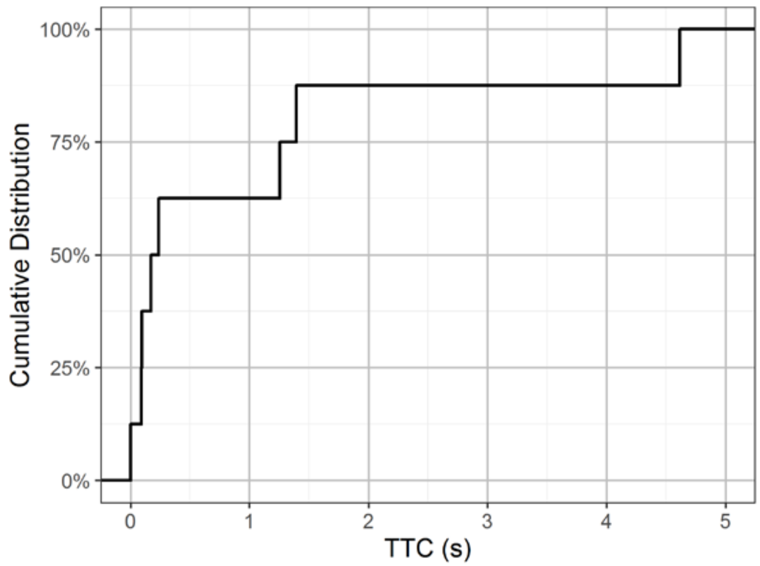

Figure 61. Cumulative distribution function of the TTC at the time of brake application post-PM in confirmed PM crashes with available brake status data.

The maximum accelerator pedal application rate, defined as the maximum difference in measured accelerator pedal position between two adjacent measurements divided by the sampling period, was also investigated and compared to the population of all crashes with accelerator pedal position data available (Figure 40). Generally, the maximum accelerator pedal application rate of PM crashes was much higher than that of all crashes. The median maximum accelerator pedal application rate of all crashes was approximately 10%/s, whereas it was approximately 114%/s for confirmed PM crashes. Crashes without any pre-crash accelerator engagement have a maximum accelerator pedal application rate of zero. Additionally, since all of the PM crashes satisfied the 25%/s threshold, the maximum accelerator pedal application rate must be at least 25%/s for PM crashes.

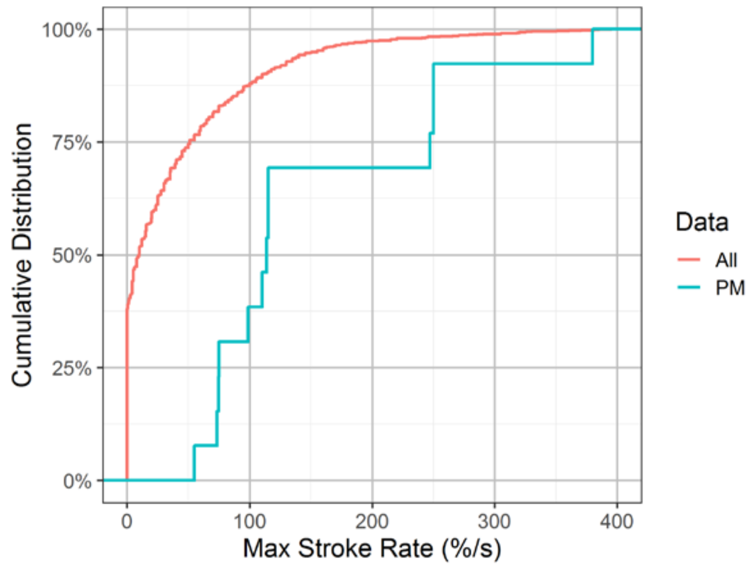

Figure 62. Cumulative distribution functions of maximum accelerator pedal application rate for all crashes and confirmed PM crashes. Maximum stroke rate could be greater than 100%/s because the sampling period was less than one second.

Within the sample of 13 confirmed PM crashes, there were two crashes where the accelerator pedal position was greater than or equal to 99% during the five second pre-crash period. This corresponds to 15.4% of the confirmed PM crashes. Additionally, among the 11 confirmed PM crashes for which braking status data was available, three crashes occurred where the driver engaged the accelerator pedal and the brake pedal simultaneously prior to impact. This corresponds to 27.3% of the confirmed PM crashes with braking status data available.

Figure 63 shows an exemplar crash in which the driver simultaneously engaged the accelerator and the brake. The vehicle was accelerating without braking for the first second, followed by approximately 1.5 seconds of no pedal engagement. Then, the brake pedal was engaged for approximately a half second before the driver engaged the accelerator pedal without releasing the brake. This simultaneous engagement of the accelerator and brake pedals persisted for approximately one second until the driver released the accelerator pedal and continued to engage the brake pedal for the final half second before impact. Within five seconds, this driver changed their pedal engagement configuration four times, corresponding to a switch rate of about 0.8 switches per second.

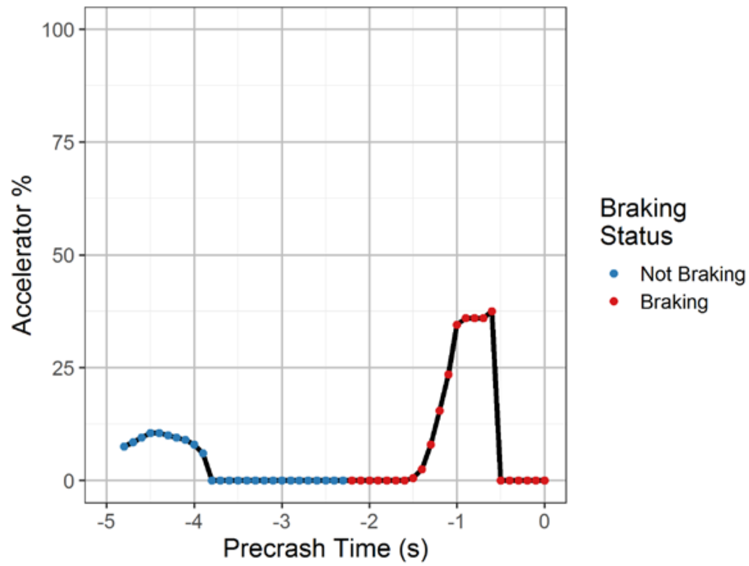

Figure 63. Time-series pedal application during the five-second pre-crash sequence of a confirmed PM crash.

After analyzing the pedal switch behavior of all confirmed PM crashes that had available brake status data, the average number of pedal switches was three, and the average switch rate was 0.6 switches per second. The cumulative distribution function of pedal switches for all confirmed PM crashes that had available brake status data is shown in Figure 64.

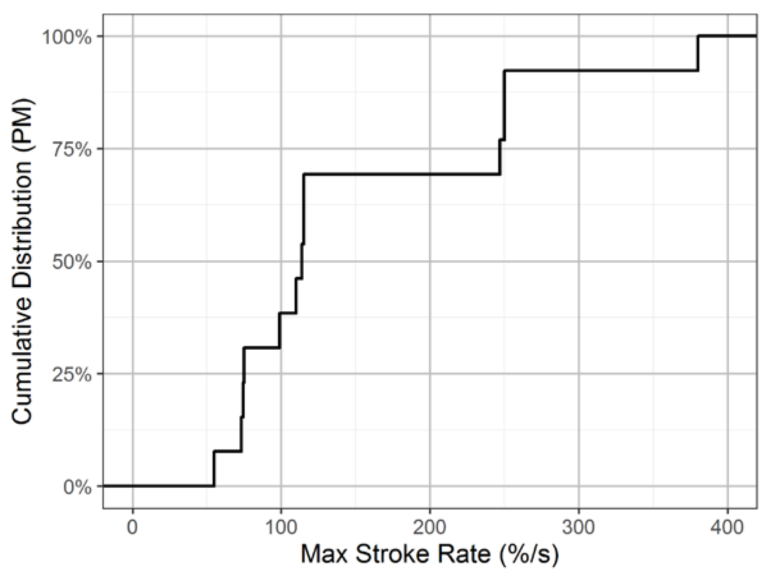

Figure 64. Cumulative distribution function of pedal switch rate among the 11 confirmed PM crashes with available brake status data.

Pedal switch rate was also investigated with respect to driver age in Table 9. Drivers 65 years and older, along with drivers younger than 25 years, typically had lower pedal switch rates than middle-aged drivers. However, it is important to note the small sample size of all age groups, most notably both the young and middle age groups.

Table 9. Summary statistics of pedal switch rate among the 11 confirmed PM crashes with brake status data available differentiated by age group.

Age Range (years)	**< 25**	**25 – 64**	**65 +**
Sample Size	1	3	7
Minimum Switch Rate	0.417	0.625	0.00
Median Switch Rate	0.417	0.833	0.625
Maximum Switch Rate	0.417	0.833	1.458
Average Switch Rate	0.417	0.764	0.598

A cumulative distribution function in Figure 65 shows the duration of accelerator pedal application after PM. Approximately half of PM drivers applied the accelerator pedal for more than a second after PM and before impact. The vehicle was considered to be accelerating if the accelerator pedal position was greater than 0%.

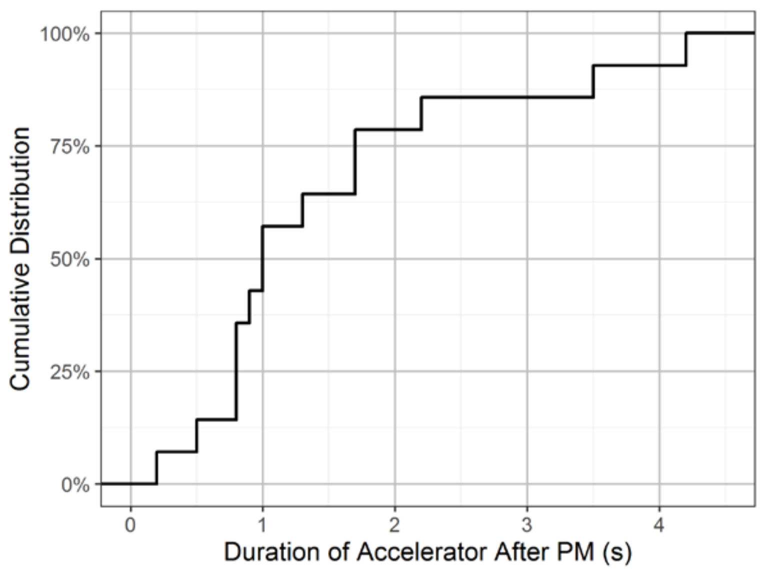

Figure 65. Cumulative distribution function of the duration of accelerator pedal application after PM among the 13 confirmed PM crashes.

Similarly, the duration of braking after PM was displayed in a cumulative distribution function in Figure 66. There were eight crashes among the 11 confirmed PM crashes with available brake status data in which the vehicle braked after PM. More than half of the PM drivers in the sample braked for less than 0.3 seconds after PM and before impact.

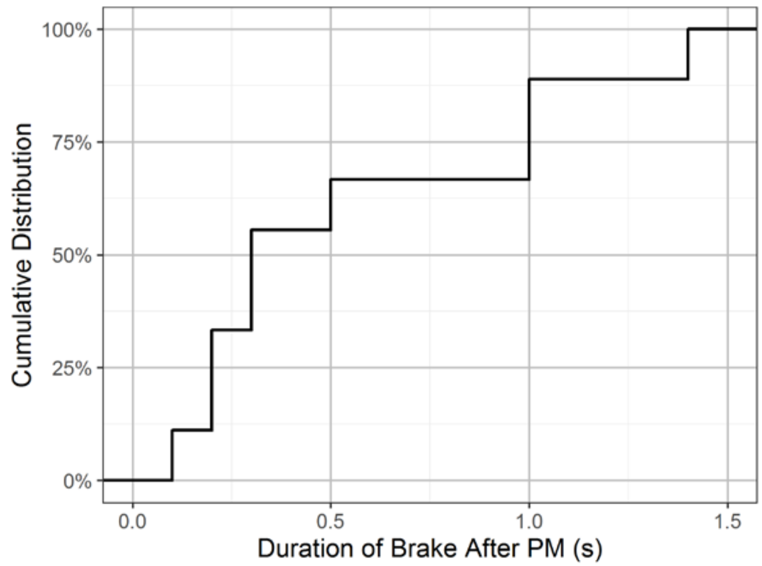

Figure 66. Cumulative distribution function of duration of brake pedal application after PM among the eight confirmed PM crashes with available brake status data in which the vehicle braked after PM.

5.4.3 Near-Crashes

The time-series data of a small subset of five PM near-crashes was evaluated in a manner consistent with the time-series data of PM crashes. The speed at PM and distance to impact were compared between confirmed crashes and near-crashes (Figure 67). Because there was no impact in a near-crash, the point of impact was approximated by the impact proximity point. In general, PMs in near-crashes occurred at greater distances from danger, occurred at a greater and wider-ranging speeds, and had longer TTCs.

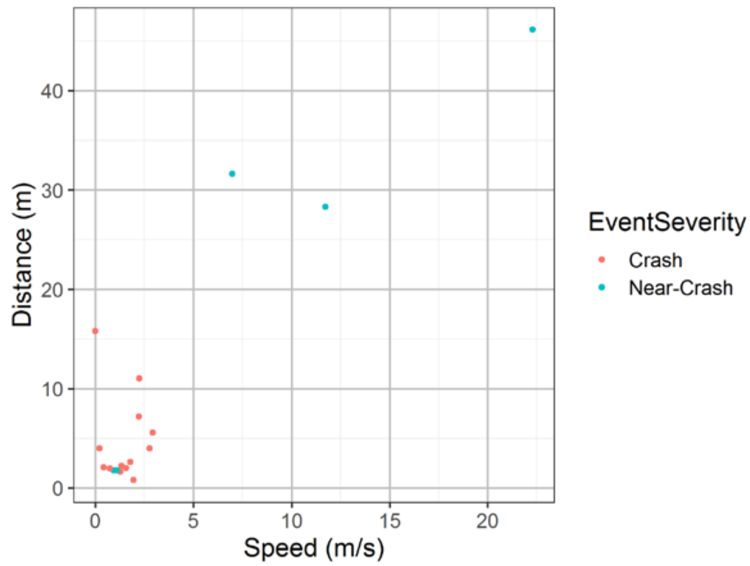

Figure 67. Scatterplot of vehicle speed against the distance to collision at the time-point of PM for each confirmed PM crash and near-crash, colored by event severity.

Additionally, to investigate the relationship between PM crashes and near-crashes, the speed ratio was calculated by taking the maximum speed the vehicle was travelling in the five seconds prior to impact divided by the speed of the vehicle at the point of PM. This represented the speed gained as a result of the PM. The speed ratio was imposed onto the events plotted previously and is shown in Figure 68. The speed ratios of confirmed PM crashes were generally higher than those of confirmed PM near-crashes.

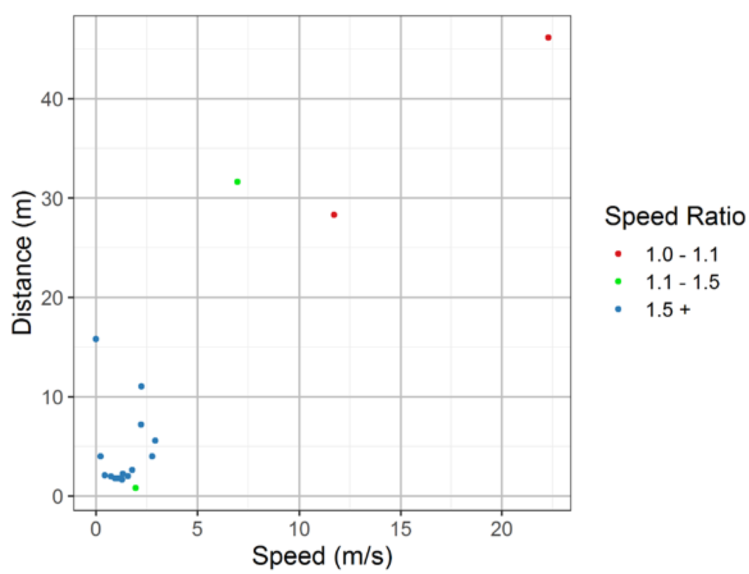

Figure 68. Scatterplot of vehicle speed against the distance to the collision at the time-point of PM for each confirmed PM crashes and near-crashes, colored by speed ratio group.

To further examine the influence of the speed ratio on near-crash and crashes, all potential PMs identified by the accelerator pedal application rate criteria were plotted in Figure 69. The results of Figure 69 support the trends seen in Figure 68, i.e., that near-crashes tended to occur at a wider range of speeds and greater distances to collision at the time of high accelerator application than crashes. Crashes were primarily plotted in the lower left quadrant of the scatterplot. To better understand the relationship between speed, distance, and event severity, the speed ratio of each event was imposed onto Figure 69, producing Figure 70. Near-crashes are observed to have a lower speed ratio than crashes. One explanation for why PM crashes occur at low speed is that, given equal accelerator pedal applications, a vehicle traveling at low speeds will accelerate more than a vehicle travelling at higher speeds. Since near-crashes have higher TTC and faster speeds, the speed ratio is also smaller.

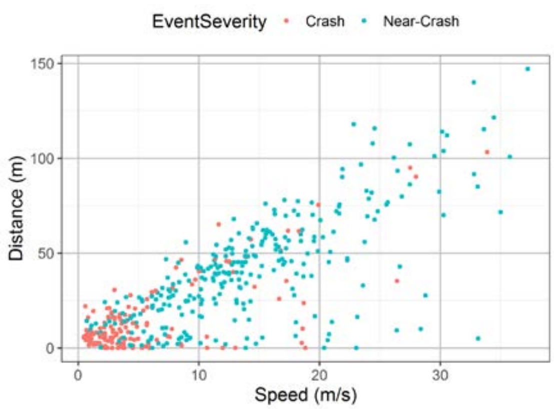

Figure 69. Scatterplot of distance to the collision against the vehicle speed at the time of PM for each potential PM crash and near crash, colored by event severity.

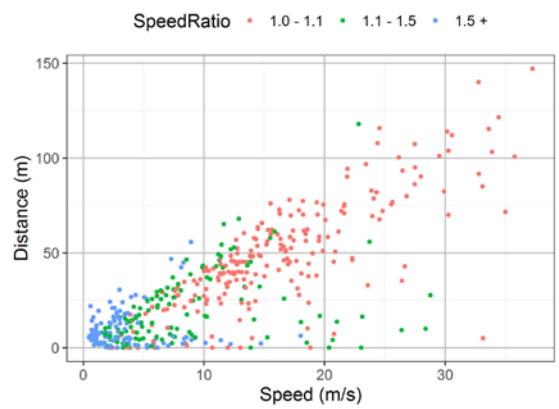

Figure 70. Scatterplot of distance to the collision against the vehicle speed at the time of PM for each potential PM crash and near crash, colored by speed ratio.

5.4.4 Crash Characteristics

Select factors were investigated among the 13 confirmed PM crashes and compared to the 1,836 total crashes in SHRP 2 NDS. Sample sizes for each particular factor after unknown values were excluded are tabulated in Table 20, included in the appendix.

The alcohol involvement variable recorded whether the driver was obviously or suspected to be under the influence of alcohol. As seen in Figure 71, there was no substantial difference in the proportion of crashes with alcohol involvement for PM crashes in comparison to all crashes.

Figure 71. Distribution of alcohol involvement among confirmed PM crashes and all crashes in SHRP 2 NDS.

The following factor recorded whether the driver was obviously or suspected to be under the influence of drugs in each crash. Figure 72 illustrates that there was no substantial difference in the proportion of crashes with drug involvement for PM crashes in comparison to all crashes

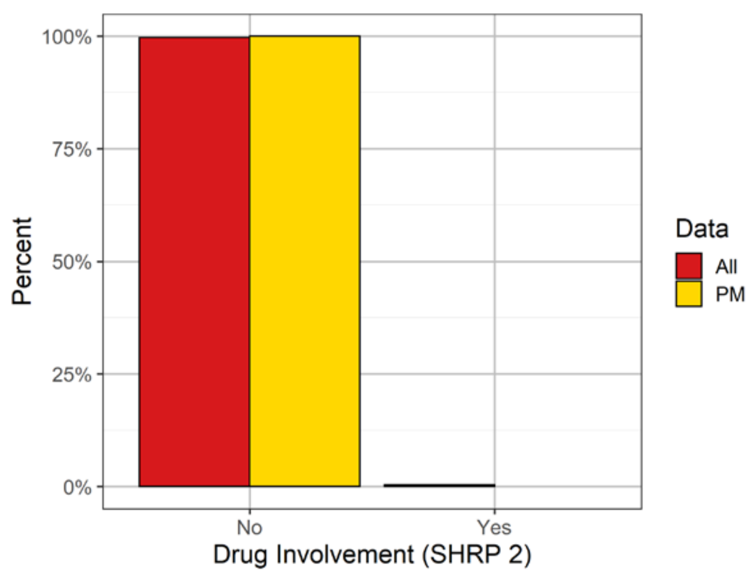

Figure 72. Distribution of drug involvement among confirmed PM crashes and all crashes in SHRP 2 NDS.

Figure 73 illustrates that the majority of PM crashes occurred at a travel speed between 0-10 kph. Over 75% of PM crashes occurred while the vehicle was travelling 10 kph or less, while only 30% of all crashes occurred while the vehicle was travelling 10 kph or less at five seconds before impact.

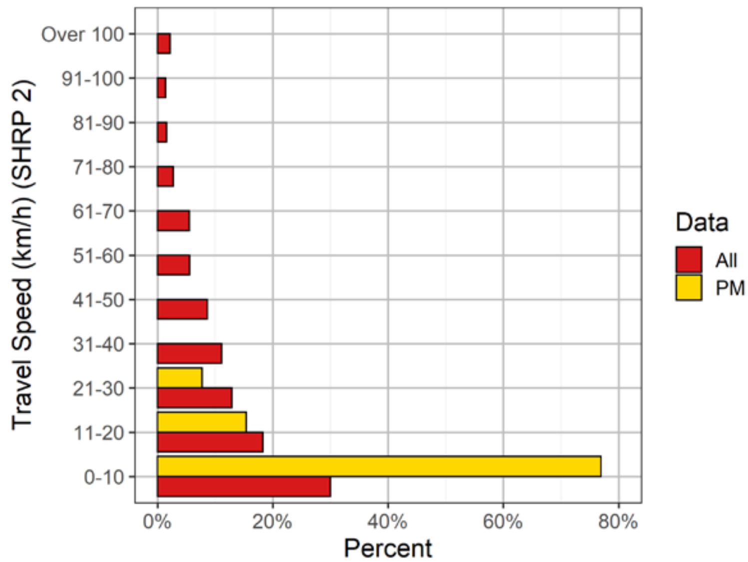

Figure 73. Distribution of travel speed among confirmed PM vehicles and all vehicles in SHRP 2 NDS crashes.

The distribution of weather factors in Figure 74 shows that a higher proportion of PM crashes occurred in no adverse conditions in comparison to all crashes. Multiple categories were combined to replicate some of the categories seen in the NASS/CDS analysis. For example, "Mist/Light Rain", "Rain and Fog", and "Rain" were all combined into a single "Rain" category.

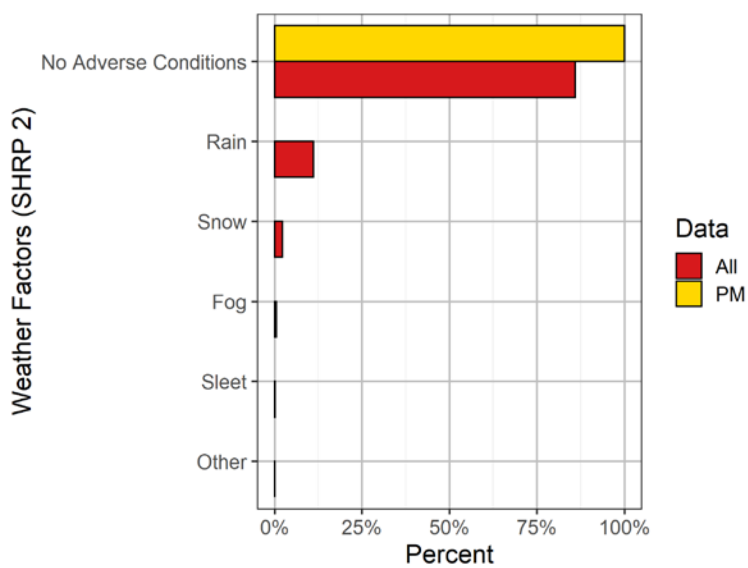

Figure 74. Distribution of weather factors among confirmed PM crashes and all crashes in SHRP 2 NDS.

The locality of crashes is categorized by the surroundings of the vehicle at the start of the precipitating event that may influence the flow of traffic. Figure 75 shows that PM crashes were approximately 12% more likely than all crashes to occur in residential locations.

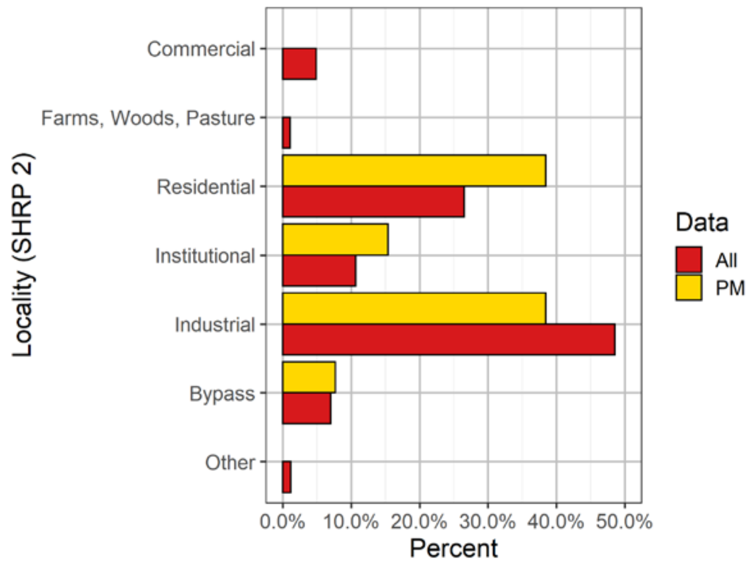

Figure 75. Distribution of locality among confirmed PM crashes and all crashes in SHRP 2 NDS.

Figure 76 presents the distribution of vehicle type and shows that the majority of vehicles in PM crashes and all crashes were passenger cars. Furthermore, the proportions of PM crashes that occurred in passenger cars and SUV crossovers were similar to all crashes.

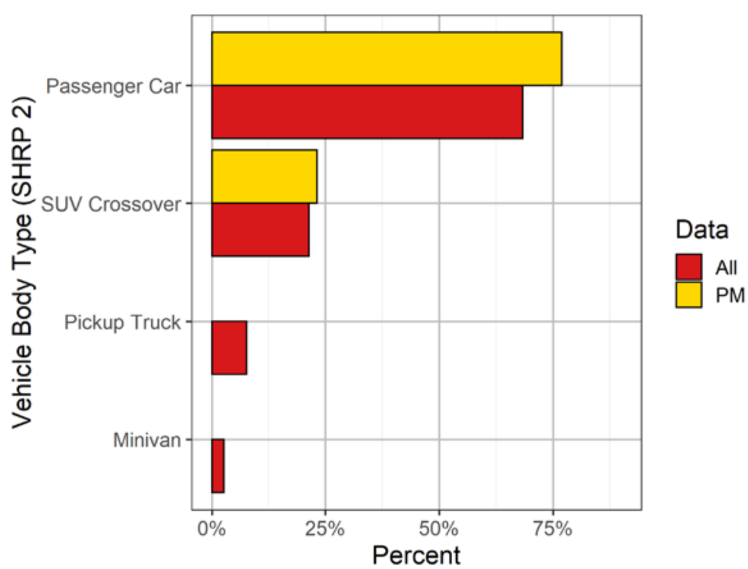

Figure 76. Distribution of vehicle body type among confirmed PM vehicles and all vehicles in SHRP 2 NDS crashes.

There was a no substantial difference in the distribution of driver distraction/inattention among drivers in PM crashes versus all crashes, shown in Figure 77. Notably, the majority of both PM crashes and all crashes involved driver distraction/inattention.

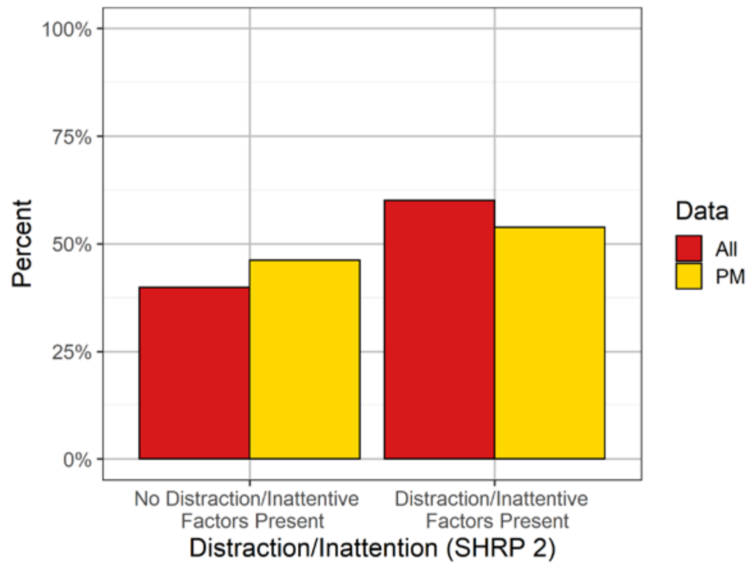

Figure 77. Distribution of driver distraction/inattention among confirmed PM crashes and all crashes in SHRP 2 NDS.

Figure 78 shows that there was no noticeable difference in the proportion of fatigued drivers in PM crashes versus all crashes. For PM crashes, there were no drivers that were indicated to be fatigued at the time of the crash.

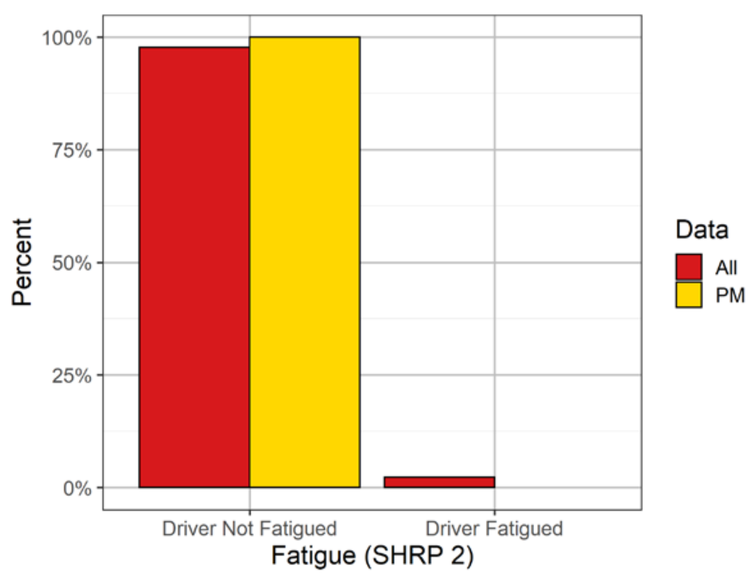

Figure 78. Distribution of driver fatigue among confirmed PM crashes and all crashes in SHRP 2 NDS.

The distribution of driver age in Figure 79 illustrates that PM crashes occurred at a noticeably higher proportion when the driver was in the 65-94 age range in comparison to all crashes. This age range involved approximately 70% of PM crashes versus less than 25% of all crashes in SHRP 2 NDS. The highest proportion of PM crashes for any single age group was committed by drivers aged 65-74 years, who accounted for over 30% of all PM crashes, whereas they accounted for only approximately 8% of all crashes.

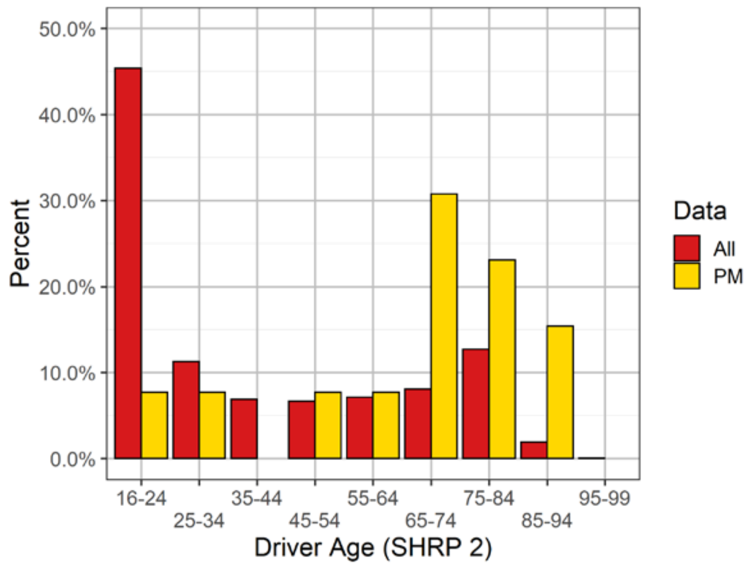

Figure 79. Distribution of driver age among confirmed PM crashes and all crashes in SHRP 2 NDS.

As illustrated in Figure 80, the majority of drivers in all crashes or who committed a PM resulting in a crash were females; however, there was no substantial difference in the sex of drivers who committed PMs that resulted in crashes in comparison to drivers in all crashes.

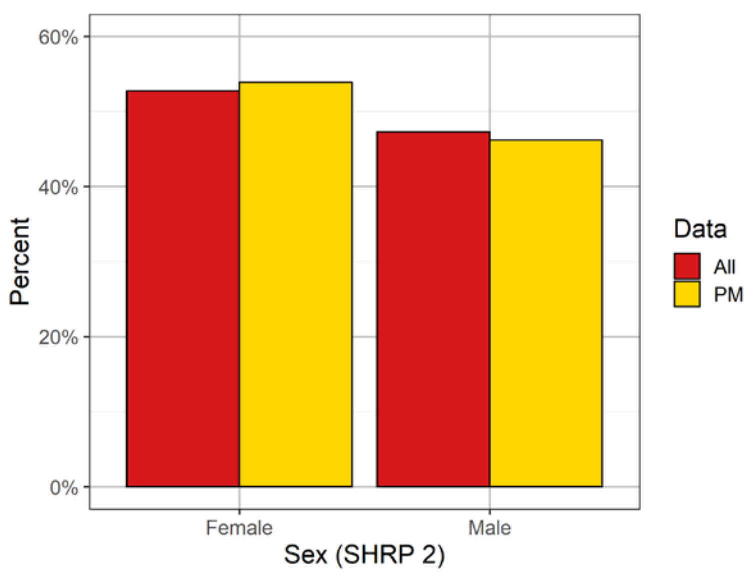

Figure 80. Distribution of driver sex among confirmed PM crashes and all crashes in SHRP 2 NDS.

5.4.5 Case Studies

Two case studies are presented. The first case study involved an attentive elderly driver pulling into a parking spot. Notably the driver entered the parking lot through the exit lane and proceeded to turn right into parking spot (Figure 81). Instead of pressing the brake pedal to come to a stop, they pressed the accelerator pedal to over 60%. The vehicle accelerated over the parking stop and curb, travelling slightly rightward. The driver pressed the accelerator pedal again to 40%, and the vehicle travelled over the sidewalk, proceeding into the grass in front of a building. The driver reached towards the ignition attempting to turn off the car and simultaneously performed an evasive steering maneuver further to the right and away from the building. The vehicle struck the right bedside panel and right rear wheel of a parked pickup truck and came to rest, nearly completing a 180˚ U-turn from the point of PM. The driver turned off the vehicle after removing their foot from the accelerator pedal while still in contact with the pickup truck. In this case, the driver did not press the brake pedal at all during the PM crash sequence. The driver forcefully pressed the accelerator pedal multiple times, resulting in the car continuing forward rather than coming to a stop. The driver's reaction to reach for the ignition instead of reevaluating their foot position could suggest that the driver believed the vehicle was malfunctioning.

Figure 81. Forward camera view in the moments before (left), during (center), and after (right) to the PM in Case Study 1.

The second case study also involved an attentive elderly driver pulling into a parking spot. The driver appeared to move their foot in preparation for braking. Without any further repositions, the driver engaged both the accelerator and brake pedals simultaneously. Once the driver realized that their vehicle was accelerating, they released both pedals and subsequently applied both pedals again. This caused the vehicle to contact a handicap sign at the end of the parking spot. In this case, the driver misapplied the accelerator pedal twice in the same event. If the first PM were prevented, it is likely to also have prevented the secondary PM and the resulting impact. The two PMs are demonstrated in the spikes of the accelerator pedal position in Figure 82. This driver switched their pedal configuration seven times within the five second pre-crash period, corresponding to a switch rate of 1.4 switches per second, much higher than the average PM switch rate of 0.6 switches per second.

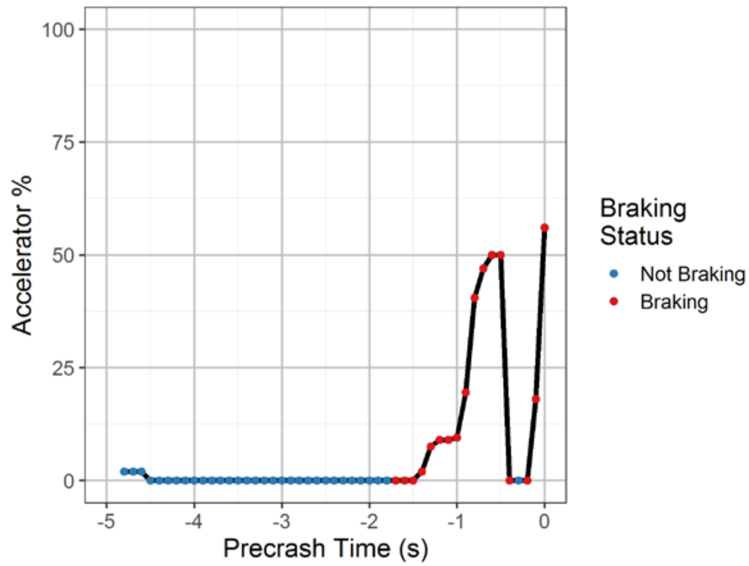

Figure 82. Time-series accelerator pedal position and brake status during the five seconds pre-crash in Case Study 2.

5.4.6 Performance of Event Data Recorder-Based Pedal Misapplication Crash Identification

When the NASS/CDS EDR PM crash identification algorithm was applied to the SHRP 2 NDS crash dataset, 145 of the 1,143 eligible crashes were identified as PM-like crashes. Of the 13 confirmed PMs, eight were correctly identified by the EDR algorithm. Table 10 illustrates how these numbers compare in a confusion matrix.

Table 10. Confusion matrix of confirmed PM crashes and PM-like crashes from the NASS/CDS EDR PM crash identification algorithm.

		EDR Algorithm		
		Not PM	PM	**Total**
Confirmed	PM	5	8	13
	Not PM	993	137	1,130
	Total	998	145	1,143

The accuracy, precision, recall, and F1 score was computed for the EDR algorithm (Table 11). The precision, accuracy, recall, and F1 score were evaluated separately for the supplemental data filters of the EDR algorithm, and then for the algorithm as a whole. This produced an accuracy of 87.6%, precision of 5.5%, recall of 61.5%, and F1 score of 0.101. The F1 score, which was the primary metric for the algorithm's performance, was ultimately improved by the cooperative application of the filters as opposed to any filter individually. Five of the 13 confirmed PM crashes would have been wrongly excluded due to filter criteria (full stop, intersection, and crash type). All five crashes were excluded by the full stop filter. One crash was excluded each by the intersection and crash type filters, though these crashes were also excluded by the full stop filter. In this small sample of 13 confirmed PM crashes, 38.5% did not fit the criteria of the EDR algorithm.

Table 11. Number of confirmed PM crashes that are included when applying each of the following filters individually. The last row displays the performance of the NASS/CDS EDR PM identification algorithm as a whole.

EDR PM Filters	Events	Accuracy	Precision	Recall	F1 Score
All Crashes	13	61.6%	2.9%	100.0%	0.056
Full Stop Filter	8	72.3%	2.5%	61.5%	0.048
Intersection/Interchange Filter	12	78.5%	4.7%	92.3%	0.089
Crash Type Filter	12	66.4%	3.0%	92.3%	0.059
All Filters	8	87.6%	5.5%	61.5%	0.101

5.5 Discussion

PM literature and Chapter 3 described analyses that estimated the frequency of PM crashes as approximately 0.2% of all crashes.[40,41,49] While the limitations of those studies methodologies suggested that the true frequency was likely higher, there was no indication of how large it may be. The rate of 4.4% found in Chapter 4 suggested that the true frequency of PM may be significantly higher than previously estimated; however, there was little data available within NASS/CDS to verify most of the identified crashes.[50] By leveraging a large-scale, long-term, in-depth naturalistic driving study, the frequency of confirmed PM crashes was determined to be 1.1% of all eligible crashes in the SHRP 2 NDS. This result was expectedly lower than the frequency of PM-like crashes identified in NASS/CDS via EDR, but notably more than five times greater than the frequencies identified from NMVCCS and the NC state crash database via crash narratives.

About half of PM crashes had a TTC at PM of at least 2 s. This result was consistent with that of Chapter 4 and remains promising. All of the PM crashes had a TTC greater than 0.45 s, the threshold identified in Kusano and Gabler's study that observed a significant reduction in crash severity in simulated rear-end crashes involving vehicles equipped with a pre-crash braking system.[14] This adds support to the suggestion that many PM crashes could be subject to such crash severity reduction if a PM countermeasure with a similar TTC activation threshold was developed.

Two drivers (15.4%) in the confirmed PM crashes engaged the accelerator to over 99%. In both of these crashes, it appeared that flooring the pedal was a direct result of pedal confusion. These represent an important subset of PM crashes because they are such extreme misapplications. Fat-footing was observed in 27.3% of the confirmed PM crashes that had available brake status data, and its analysis provides a value for the proportion of drivers who committed a PM due to erroneous foot placement on both pedals. Further, there was extensive pre-crash pedal switching. With more pedal switches, the odds of misapplying a pedal increase because the driver is exposed to more opportunities to place their foot in the wrong place. Conversely, after a PM, it is expected that a driver would react by correcting their misapplication if they have time, thereby increasing the number of switches. Both of these are possible justifications for the increased average pedal switch rate of 0.63 switches per second pre-crash among the 11 confirmed PM with available brake data.

Before analyzing and comparing the crash characteristics of the confirmed PM crashes of SHRP 2 NDS, it was important to consider that SHRP 2 NDS was neither a representative sample, nor did it contain similar crash inclusion criteria to those of NMVCCS, the NC state crash database, and NASS/CDS. SHRP 2 NDS purposefully oversampled drivers who were exposed to greater crash risk, such as older and younger drivers. Additionally, crashes were defined in SHRP 2 NDS as any time vehicle contact with an object was recorded/detected.[109] This was in stark contrast to the tow-away criteria of NMVCCS and NASS/CDS, and slightly less restrictive than the NC state crash database's criteria of injury or property damage greater than $1,000. Therefore, the samples obtained from each of the databases represented different crash populations with both unique and similar characteristics. This effect of these differences should be weighed before drawing conclusions regarding how the analyses compare with one another or the characteristics of PM crashes generally.

In terms of the crash characteristics recorded in SHRP 2 NDS, the effects of alcohol or drugs, weather factors, or vehicle type did not appear to contribute to PM crashes. There was no considerable difference in proportions of PM crashes among these factors as compared to all crashes, in agreement with the trends observed in the NMVCCS, NC state crash database, and NASS/CDS data. It was noteworthy that SHRP 2 NDS only considered crashes in passenger vehicles, including passenger cars, SUV crossovers, pickup trucks, and minivans. In NMVCCS and NASS/CDS, it was required that at least one vehicle involved in the crash be a passenger vehicle to be included in the database. Inherently, the samples were targeted primarily – if not exclusively – at passenger vehicles. The characteristics of PM crashes among other vehicle types are likely to be underrepresented as a result.

PM crashes in SHRP 2 NDS occurred at substantially lower travel speeds relative to all crashes. This pattern concurred with the results found in NMVCSS and the NC state crash database, though the sample of PM-like crashes from NASS/CDS revealed the opposite. NASS/CDS data may have produced more high-speed PM-like crashes due to database crash inclusion criteria and/or the full stop and intersection/interchange filters. The results of the near-crash investigation suggest that this may be due to the speed ratios associated with low-speed PMs. A vehicle traveling 10 mph easily accelerates to 15 mph as a result of a heavy PM, which increases the odds that the vehicle reaches speeds in excess of those for which the low-speed environment (e.g., a parking lot or residential street) is designed. A vehicle travelling at freeway speeds, limited by the power output of its engine, may only accelerate by 1-2 mph when a similar PM is committed. This would be less likely to bring the vehicle to dangerous speeds relative to the roadway design.

The proportion of PM crashes that occurred in residential locations was significantly higher than that of all crashes. This could be related to the capture of less severe PM crashes relative to the other databases. The database with the most similar crash inclusion criteria, the NC state crash database, also had an overrepresentation of PM crashes in residential areas.

Drivers involved in PM crashes in SHRP 2 NDS were characterized as slightly more likely to be female than male. Unlike any other database analyzed, drivers in all crashes were more likely to be female, though the distribution was slightly more dramatic among PM crashes. Females were slightly overrepresented among the 3,241 SHRP 2 NDS primary participants. The sex distribution of PM drivers agreed with results from the NC state crash database and NMVCCS data; however, NASS/CDS characterized PM drivers as more likely to be male. SHRP 2 NDS PM drivers were also older as compared to drivers in all crashes, particularly in the age range of 65-94 years old. An increased prevalence of younger drivers committing PMs was not observed in SHRP 2 NDS, unlike what was seen in NMVCCS and NASS/CDS.

PM near-crashes seemed to follow similar patterns as crashes overall; however, the driver was able to recover from the PM in near-crashes. In PM near-crashes the speed of the vehicle at the point of PM tended to be higher than in PM crashes. Additionally, the speed ratio of potential PM near-crashes was lower than that of potential PM crashes.

5.5.1 Common False Positives

The crashes identified as potential PMs (both crashes and near-crashes) from accelerator pedal application rate filter that were manually reviewed and ultimately confirmed to *not* be PMs tended to follow one of a few common scenarios. The first involved a subject vehicle behind a lead vehicle stopped at a red light on a multi-lane road. The ambient traffic in the neighboring lane accelerated (e.g., as a result of a lane-specific traffic signal such as a left turn arrow). Often, the subject driver was distracted by a phone or something else in the car, or they were looking behind them. When the driver recognized the movement of the ambient traffic, they accelerated without looking forward at the lead vehicle and caused a crash or near-crash. This same theme occurred whether the subject vehicle was in a turn lane and the through lane signal changed, or vice versa. A variant of this scenario occurred when a subject distracted driver glanced up and noticed the lead vehicle had begun to move. They pressed on the accelerator, returned their attention to the distraction, failed to recognize that the lead vehicle stopped again, and caused a crash or near-crash. Another similar scenario occurred when the subject vehicle approached an intersection or interchange behind a lead vehicle. While waiting for the yielding lead vehicle to make their turn, the subject driver looked not at a distraction, but rather over their shoulder to analyze for cross traffic in preparation for their own turn. Upon observing no oncoming cross-traffic, the subject driver assumed the lead vehicle had already entered the crossroad, and they proceeded to accelerate and begin their turn. When the lead vehicle did not make the turn, the subject vehicle collided into the back of the lead vehicle.

The pedal applications in these events were determined by the investigating researchers to be intentional and, therefore, not a PM. These inappropriate pedal applications appear similar to unintentional pedal applications, indicating that similar crash prevention methods could be employed to mitigate and prevent both types of crashes.

5.5.2 Narrative Identification

VTTI identified 10 potential PM crashes and 10 potential PM near-crashes based on an independent keyword search. Of these events, only five crashes and three near-crashes were identified as potential PMs by replicating the keyword search method of Chapter 3. All 20 events were manually inspected, and seven crashes and five near-crashes were confirmed as PMs. Of these seven narrative-confirmed PM crashes, four were identified from the acceleration pedal application rate analysis. Of the five narrative-confirmed PM near-crashes, two were identified as from the accelerator pedal application rate analysis. The discrepancy in events identified as PMs via the narrative and the accelerator pedal application rate data was due to either missing or misaligned accelerator pedal position data.

5.5.3 Limitations

The SHRP 2 NDS was not quite a representative sample of crashes and purposefully oversampled particular factors. This slightly restricts the ability of the calculated PM crash frequency in SHRP 2 NDS to be generalized to larger populations.

Because accelerator pedal position data and vehicle speed data were needed to identify potential PMs and analyze PMs, cases in which this data was not available were not able to be analyzed. Vehicle network speed, i.e., tire speed, was chosen as the data source for vehicle speed, as opposed to GPS-determined speed. In times when traction is lost, network speed may not reflect the true speed of the vehicle. When the vehicle is tracking, the error is negligible. Network speed was used because it had a higher sampling frequency than GPS speed, but limits the calculations based on vehicle speed to the extent that the network speed did not capture the true vehicle speed. Additionally, it is important to note that the sampling frequency of pre-crash data elements was generally higher than that of the EDRs of NASS/CDS. Since the SHRP 2 NDS data acquisition system measures data in 0.1 s intervals, the application of this method to this data identifies potential PMs with a minimum increase in acceleration pedal position of 2.5% in 0.1 seconds. While this is proportional to the functional requirement of EDR data to have an increase of accelerator pedal position of either 12.5% or 25% in 0.5 s or 1.0 s, respectively, it could result in a discrepancy in the types of events marked as potential PMs. This does not affect the validity of the 13 confirmed PMs, as all of them were ultimately verified by video review, but may have a small effect on cases identified as potential PMs, i.e., those analyzed in Figure 69 and Figure 70.

Lastly, none of the confirmed SHRP 2 NDS PM crashes met the NASS/CDS inclusion criteria, i.e., a crash on a public road involving at least one vehicle towed due to damage. This severely restricts the ability of the performance evaluation of the EDR algorithm conducted using SHRP 2 NDS data to be reapplied to the NASS/CDS data to estimate true PM crashes from PM-like crashes. In other words, the algorithm can be evaluated for all crashes as represented in SHRP 2 NDS, but not specifically for NASS/CDS crashes.

5.6 Conclusion

This study has evaluated a novel alternative for PM crash identification developed and applied in Chapter 4 to supplement previous crash narrative keyword searches of Chapter 3. This method identified potential PM crashes through a data acquisition system in which time-series data was not limited by the content of crash narratives. Moreover, video footage from the potential PMs were able to be manually reviewed simultaneously with graphs of accelerator pedal position, vehicle speed, and brake status data to confirm the presence of a PM. After analyzing SHRP 2 NDS pre-crash data alongside event videos, PMs were observed in 1.1% of all eligible crashes. This result was substantially higher than previously estimated PM crash frequencies, though lower than suggested by NASS/CDS EDR data. Additional pedal behaviors, such as pedal flooring, simultaneous pedal engagement, and pedal switching, were analyzed to investigate the pedal dynamics surrounding PMs.

Further characteristics of these crashes were analyzed in a manner consistent with that of the previous three analyses and compared to the population of all crashes recorded in SHRP 2 NDS. While many of the characteristics followed similar trends as those of PM crashes in the previous databases, the SHRP 2 NDS PM crashes were observed to trend toward older, female drivers traveling at lower speeds.

Chapter 6: Estimating the Safety Benefit of a Theoretical Pedal Misapplication Advanced Driver Assistance System

6.1 Introduction

The final study of this thesis seeks to evaluate the safety benefit of a theoretical acceleration suppression system designed to prevent or mitigate PM crashes by developing a vehicle dynamics simulation informed by real-world, confirmed PM crash data. These crash scenarios were generated with crash data from a national, representative crash causation study and detailed, time-series pedal data from a large-scale, long-term, in-depth naturalistic driving study. They were simulated in Python with and without a theoretical PM identification and accelerator suppression system. A variety of system activation thresholds were investigated, and both crash avoidance and crash mitigation were used to estimate the ultimate safety benefit.

6.2 Data Sources

The data sources leveraged for this study were NMVCCS and SHRP 2 NDS. Specifically, a set of 22 of the 33 confirmed PM crashes identified from NMVCCS via the keyword search method as described in Chapter 3 and the set of 13 confirmed PM crashes identified from SHRP 2 NDS via time-series data analysis and manual video review as described in Chapter 5 were used. NMVCCS was selected for its detailed crash data, including crash scene diagrams from which impact locations and vehicle final rest locations could be determined. SHRP 2 NDS was selected for its video data which allowed for confirmation of PM crashes and its high-resolution time-series pedal activation data.

6.3 Methods

6.3.1 Case Selection

Detailed descriptions of the data sources and identification methods for NMVCCS and SHRP 2 NDS PM crashes are provided in Chapter 3 and 5, respectively. The cases selected from the NMVCCS confirmed PM crashes were further restricted by the ability to reconstruct the crash delta-V. This is further outlined in the following section. Ultimately, the analysis was restricted to 22 of the 33 original confirmed PM crashes. All 13 of the confirmed PM crashes identified in SHRP 2 NDS were used.

6.3.2 Determining Crash Delta-V

The PM crashes identified in NMVCCS served as the foundation for the simulations. PC-Crash was utilized to reconstruct each NMVCSS crash profile. The make and model of the vehicles in the crash provided in NMVCCS were selected in PC-Crash and assigned the appropriate vehicle dimensions and properties for reconstruction. Additionally, the weight of the occupants and cargo as provided in NMVCCS were added to the vehicle. For cases in which the weights of the occupants were unknown, the weight of the Hybrid III 50th percentile male, the Hybrid III 5th percentile female, or the Hybrid III children models were substituted. Friction factors determined from NMVCCS road surface condition data ($\mu = 0.7$ for dry conditions, $\mu = 0.4$ for wet conditions) were implemented into PC-Crash to improve the accuracy of the model. With the provided variables, the collision optimizer reconstructed the impact velocity and delta-V based on the impact locations and final rest locations. Ten cases were excluded on account of incomplete data (e.g., no scale on scene diagram) or complex impact dynamics (e.g., rollover, guardrail impact, multiple impacts) that made reconstruction in PC-Crash prohibitive (Table 12). Three cases (one additional case not already excluded) could not be simulated because the PM occurred after the initial impact. This resulted in 22 reconstructed PM crashes eligible for simulation.

Table 12. NMVCCS crash exclusion.

NMVCCS Case ID	Reason for Exclusion
2005012694482	*No scale.* The crash scene diagram was not properly scaled.
2005013698221	*Multiple impacts.* Vehicle contacted a large tree then impacted a fence before impacting a full-size van which is pushed into a house.
2005074596521	*Multiple impacts.* Vehicle, in reverse, crashed into two traffic signal poles, into a wood picnic table and through the exterior wall of a restaurant.
2006002585246	*Tire failure and PM after impact.* Vehicle tire failed. The air bag deployed after the vehicle contacted curb which obstructed the driver's view and resulted in a PM.
2006011268644	*Embankment*. Vehicle departed the road to the right. The driver overcorrected and departed the road to the left. The vehicle impacted an embankment and a fence.
2006041513621	*Multiple impacts.* While making a left turn, the vehicle departed the road and struck a bus bench, an awning post, a few bushes, and a signpost.
2007004866928	*Multiple impacts and PM after impact*. While negotiating a curve, the vehicle struck a curb and departed the road. Then, the PM occurred, and the vehicle proceeded to strike a guide wire and a tree.
2007006589948	*Trailer disconnected*. A vehicle towing a trailer was driving when the driver lost control of the trailer and the trailer jackknifed then became disconnected and trailer flipped onto its side. The driver then committed the PM.
2007011583008	*Guardrail impact*. The vehicle departed the road to the right and impacted a metal guardrail. It proceeded to impact a chain link fence and a wooden post.
2007041600907	*PM after impact.* Vehicle 1 ran a red light and struck another vehicle. After impact the driver of vehicle 1 hit the gas instead of the brakes and continued across the intersection and impacted the curb.
2007045403229	*Rollover*. The vehicle departed the road on the right before crossing into the other lane and departed the road to the left. It impacted a ditch before it impacted a fence caused the vehicle to roll over 6 quarter turns.

6.3.3 Determining Parameters at Pedal Misapplication

Beginning from the point of impact as reconstructed in PC-Crash, the vehicle dynamics were simulated in reverse until the time of PM.

The vehicle dynamics of the 22 NMVCCS cases were reverse-simulated in Python from the point of impact, as determined by PC-Crash, to the point of PM using each of the 13 SHRP 2 NDS pedal profiles. The position, velocity, acceleration, and normal forces of the vehicle were calculated at each timestep to determine parameters at the point of PM. These parameters formed 286 unique initial conditions as the basis for the forward simulations.

The reverse-simulation operated with a timestep of 0.01 s. Because the SHRP 2 NDS pedal profile data was collected at 10 Hz, the pedal inputs in between datapoints were set as the previously known value. For example, if the accelerator pedal application at -0.50 s was 17%, the accelerator pedal application for -0.49 s, -0.48 s, -0.47 s, …, -0.41 s was assumed to be 17% until it updated at -0.40 s with the more recent value. Based on the braking status in these pedal profiles, the acceleration due to braking was calculated using a jerk of 11 m/s^3 and a maximum braking deceleration of 0.4 g (3.92 m/s^2). Using these pedal profiles, the vehicle dynamics were simulated. All vehicles were assumed to have only two axles and generate no lift or downforce. The environment was assumed to be sea-level with a temperature of 72°F and a constant grade. Parameters of the vehicle and environment are listed in Table 13.

Table 13. Simulation parameters for vehicle and environment.

Parameter	Symbol	Definition	Value
Gravity	g	Acceleration due to gravity	9.81 m/s^2
Mass	m	Mass of the vehicle, occupants, and cargo	Vehicle-specific
Weight Distribution	k	Proportion of weight which rests on the rear axle	37%
Wheelbase	L	Longitudinal distance (m) from rear axle to front axle	Vehicle-specific
Height of Center of Gravity	h_{cg}	Height (m) of the vehicle's center of gravity	Vehicle-specific
Height of Center of Pressure	h_{cp}	Height (m) of the vehicle's center of pressure	Vehicle-specific
Rolling Resistance	f	Coefficient of a combination of forces which resist the rolling motion of a body on a surface	0.015
Aerodynamic Drag	C_dA	The product of the drag coefficient and the frontal area of the vehicle (m^2)	Vehicle-specific
Engine Power	P_{engine}	The peak power output of the vehicle (kW)	Vehicle-specific
Throttle Position	$\mu_{throttle,i}$	Position of the throttle, assumed to be equal to the accelerator pedal position	0-100%
Air Density	ρ	The density of air	1.195 kg/m^3

Parameter	Symbol	Definition	Value
Grade	θ	The angle between the vehicle normal and a line from the vehicle center to the Earth's center	Environment-specific
Power Split	P_r	Proportion of engine power delivered to the rear axle	100% for rear-wheel drive 0% for front-wheel drive 10% for all-wheel drive
Tire Friction	μ	Maximum tire friction	0.7 for dry conditions 0.4 for wet conditions
Simulation Timestep Length	dt	Length of time between loops	0.01 s
Simulation Timestep Index	i	Current simulation loop	0-999
Normal Force, Front	$N_{f,i}$	Downward force on the front axle	Dynamic
Normal Force, Rear	$N_{r,i}$	Downward force on the rear axle	Dynamic

The vehicle dynamics were simulated as follows. First, the simplified assumption was made that the accelerator pedal position was equal to the throttle position which determined the proportion of power produced by the engine (Equation 5). A 0% throttle produced no power, and a 100% throttle produced maximum engine power.

$$P = P_{engine}\mu_{throttle,i} \tag{5}$$

The rolling resistance force on the vehicle is given for the front and rear axles by Equations 6 and 7.

$$F_{rr,f} = fN_{f,i} \tag{6}$$
$$F_{rr,r} = fN_{r,i} \tag{7}$$

The drag force on the vehicle is given by Equation 8 where *v* is the velocity of the vehicle.

$$F_d = \frac{1}{2}\rho C_d A v_k^2 \tag{8}$$

The grade force, due to climbing or descending a hill, is given by Equation 9.

$$F_g = mg\sin\theta \tag{9}$$

The engine force for the front and rear axles is given by Equations 10 and 11 where $a_{brake,i}$ was determined by the braking pedal profile with a jerk rate of 11 m/s^3 and a maximum braking acceleration magnitude of 0.4 g.

$$F_{e,f} = \frac{P}{v_k}(1 - P_r) + 0.7ma_{brake,i} \tag{10}$$

$$F_{e,r} = \frac{P}{v_k}(P_r) + 0.3ma_{brake,i} \tag{11}$$

The maximum tires forces are given by Equations 12 and 13 but the actual tire forces are whichever is lower between Equations 14 and 15.

$$F_{tmax,f} = \mu N_{f,i} \tag{12}$$
$$F_{tmax,r} = \mu N_{r,i} \tag{13}$$
$$F_{x,f} = \min\left(F_{e,f}, F_{tmax,f}\right) \tag{14}$$
$$F_{x,r} = \min\left(F_{e,r}, F_{tmax,r}\right) \tag{15}$$

Euler integration of acceleration is performed with Equations 16 to 18.

$$t_{i+1} = t_i + dt \tag{16}$$
$$v_{i+1} = v_i + a_{i+1}dt \tag{17}$$
$$x_{i+1} = x_i + v_{i+1}dt \tag{18}$$

Then, the new acceleration is computed by Equation 19.

$$a_{i+1} = \frac{F_{x,f} + F_{x,r} - F_{rr,r} - F_{rr,f} - F_d - F_g}{m} \tag{19}$$

The rear normal force on the vehicle is computed by Equation 20 which is then used to compute the front normal force in Equation 21.

$$N_{r,i+1} = mgk + \frac{\left(F_{x,f} + F_{x,r} - F_{rr,r} - F_{rr,f} - F_g\right)h_{cg}}{L} + \frac{F_d h_{cp}}{L} \tag{20}$$
$$N_{f,k+1} = mg - N_{r,i+1} \tag{21}$$

To verify the results of the reverse-simulation, the vehicle parameters at the point of PM were used as initial conditions in a separate forward-simulation. The pedal profiles remained unchanged, and the time and speed of the vehicle at the point of impact were evaluated for each of the combinations to confirm whether the vehicle dynamics of the reverse- and forward-simulations were consistent. All original crash reconstructions were accurately simulated within 0.01 s of the original crash time and within 0.1 m/s of the original impact speed.

For 13 of the 286 original NMVCCS crash/SHRP 2 NDS pedal profile combinations, the simulated PM speed was less than or equal to 0 m/s. This meant that there existed no forward speed the vehicle could have been traveling at the point of PM to result in the calculated impact speed given by that particular pedal profile. These cases were excluded from analysis, leaving a total of 273 crash scenarios.

6.3.4 Accelerator Suppression

An accelerator suppression system was added to the forward-simulation to assess its potential safety benefit. The modeled system evaluated six conditions before activating:

1. *Accelerator Pedal Application Rate*: the accelerator pedal application rate must have been greater than or equal to the threshold value.
   - Determined by SHRP 2 NDS pedal profile data.
   - Threshold values simulated: 10%/s, 25%/s, 50%/s, 75%/s, 100%/s, 250%/s, 500%/s.
2. *Pedal Position*: the accelerator pedal position must have been greater than or equal to the threshold value.
   - Determined by SHRP 2 NDS pedal profile data.
   - Threshold values simulated: 0%, 25%, 50%, 70%, 75%, 80%, 90%.
3. *Vehicle Speed*: the vehicle must have been traveling equal to or faster than the threshold value.
   - Determined by simulated vehicle dynamics.
   - Threshold values simulated: 0 kph, 30 kph, 60 kph.
4. *Recent Braking*: the vehicle must not have engaged the brake within a specified time prior to system activation.
   - Determined by SHRP 2 NDS pedal profile data.
   - Threshold value simulated: 0.0 s, 0.5 s, 1.0 s, 2.0 s.
5. *Grade*: the vehicle must not have been traveling on an uphill grade.
   - Determined by NMVCCS grade variable, which only indicated whether the vehicle was traveling on a negative, level, or positive grade.
6. *Turning*: the vehicle must not have had its turn signal activated.
   - Determined by researcher judgment based on NMVCCS scene diagram.

All of the activation conditions were evaluated at each timestep. If all of the conditions were met, the system would activate. Once activated, acceleration pedal input was immediately suppressed, i.e. defined as zero. The braking profile remained unchanged to account for cases where the driver switched from the accelerator to the brake. If the accelerator suppression system activated, the simulation generally lasted longer than the simulation of the original crash because the vehicle was moving slower. Because the pedal profile data was only applicable up until the time of the original crash, the pedal inputs after the original impact point were assumed to remain constant from the last recorded pedal inputs. In other words, if the driver was braking at the time of the original crash, they were assumed to hold that braking position beyond the time of the original crash in the extended accelerator suppression simulations. In total, 137 versions of the system with unique combinations of activation thresholds were implemented in the simulations.

6.3.5 Computing Safety Benefit

If the system did not activate, the crash occurred as originally modeled. Each simulation for which the system did activate had the potential to result in one of three outcomes: the vehicle crashed at the same time as in the original crash, crashed later than in the original crash, or stopped before the crash. A crash was considered to have occurred at the same time as in the original crash if it was within 0.05 s of the original crash time. A fourth option existed, which was that the simulation timed out. For computational efficiency purposes, each simulation was allowed to simulate a maximum of 10 s post-PM. If the vehicle had neither come to a stop nor travelled the distance required to crash at 10 s post-PM, the simulation timed out. These simulations involved vehicles coasting at low speeds (< 9 mph) with no brake input, only being slowed by drag or grade forces. For the purpose of the analysis, we assumed that a driver who had committed a PM and did not experience any resultant deceleration or acceleration (i.e., they pressed the accelerator pedal and acceleration was suppressed by the system) would eventually respond with braking within 10 s and, therefore, the crash would be avoided. Thus, these cases were joined with the "stopped before the crash" group.

Because the system only suppressed acceleration input and neither automatic braking nor driver braking response was modelled, it was predicted that many crashes would still occur with activation. To estimate how many crashes would be prevented with braking, the distance required to stop the vehicle at the point of activation was calculated for each applicable case and compared to the distance to the crash at the point of activation.

The safety benefit of the system is dependent on how often it activates in response to a PM. The activation criteria were investigated by calculating the weighted activation rate and crash avoidance rate for each combination of system thresholds. The effect of system activation on crash prevention and crash mitigation was analyzed by calculating impact speed reduction, i.e., the difference between the original impact speed and the reduced impact speed after activation. The impact speed reduction was equal to the original impact speed in the event of crash avoidance.

6.4 Results

Each of the 22 NMVCCS impacts were successfully reconstructed in PC-Crash and produced an average impact speed of 52.4 kph (32.6 mph). The PM speeds of all combinations of NMVCCS and SHRP 2 NDS PM crashes were obtained through the reverse vehicle dynamics simulation. On average, the PM occurred 1.76 s before the original crash at an average speed of 49.5 kph (30.8 mph).

The 273 crashes were successfully simulated with each of the 137 unique acceleration suppression system variations, resulting in 37,401 PM scenarios. Table 14 tabulates the activation and crash avoidance rate for some of the more-conservative threshold combinations. Among these combinations, none of the activation rates exceeded 11% and no crashes were avoided.

Table 14. Percent of weighted cases in which the accelerator suppression system activated for a variety of conservative threshold combinations. Grade and turning values were not time-dependent and were based on NMVCCS data.

SYSTEM THRESHOLDS						**SYSTEM PERFORMANCE**	
Pedal Position (%)	**Stroke Rate (%/*s*)**	**Vehicle Speed (*kph*)**	**Recent Braking (*s*)**	**Grade (%)**	**Turning**	**Activated (%)**	**Crashes Avoided (%)**
70	100	15	0	0	No	10.8	0.0
70	100	15	1	0	No	7.7	0.0
70	100	15	2	0	No	7.7	0.0
70	100	30	0	0	No	10.1	0.0
70	100	30	1	0	No	7.2	0.0
70	100	30	2	0	No	7.2	0.0
70	100	60	0	0	No	3.5	0.0
70	100	60	1	0	No	2.5	0.0
70	100	60	2	0	No	2.5	0.0
70	250	15	0	0	No	0.0	0.0
70	250	15	1	0	No	0.0	0.0
70	250	15	2	0	No	0.0	0.0
70	250	30	0	0	No	0.0	0.0
70	250	30	1	0	No	0.0	0.0
70	250	30	2	0	No	0.0	0.0
70	250	60	0	0	No	0.0	0.0
70	250	60	1	0	No	0.0	0.0
70	250	60	2	0	No	0.0	0.0
70	500	15	0	0	No	0.0	0.0
70	500	15	1	0	No	0.0	0.0
70	500	15	2	0	No	0.0	0.0
70	500	30	0	0	No	0.0	0.0
70	500	30	1	0	No	0.0	0.0
70	500	30	2	0	No	0.0	0.0
70	500	60	0	0	No	0.0	0.0
70	500	60	1	0	No	0.0	0.0
70	500	60	2	0	No	0.0	0.0
80	100	15	0	0	No	4.8	0.0
80	100	15	1	0	No	4.8	0.0
80	100	15	2	0	No	4.8	0.0
80	100	30	0	0	No	4.4	0.0
80	100	30	1	0	No	4.4	0.0
80	100	30	2	0	No	4.4	0.0
80	100	60	0	0	No	1.2	0.0
80	100	60	1	0	No	1.2	0.0
80	100	60	2	0	No	1.2	0.0
80	250	15	0	0	No	0.0	0.0
80	250	15	1	0	No	0.0	0.0

SYSTEM THRESHOLDS						SYSTEM PERFORMANCE	
Pedal Position (%)	**Stroke Rate (%/*s*)**	**Vehicle Speed (*kph*)**	**Recent Braking (*s*)**	**Grade (%)**	**Turning**	**Activated (%)**	**Crashes Avoided (%)**
80	250	15	2	0	No	0.0	0.0
80	250	30	0	0	No	0.0	0.0
80	250	30	1	0	No	0.0	0.0
80	250	30	2	0	No	0.0	0.0
80	250	60	0	0	No	0.0	0.0
80	250	60	1	0	No	0.0	0.0
80	250	60	2	0	No	0.0	0.0
80	500	15	0	0	No	0.0	0.0
80	500	15	1	0	No	0.0	0.0
80	500	15	2	0	No	0.0	0.0
80	500	30	0	0	No	0.0	0.0
80	500	30	1	0	No	0.0	0.0
80	500	30	2	0	No	0.0	0.0
80	500	60	0	0	No	0.0	0.0
80	500	60	1	0	No	0.0	0.0
80	500	60	2	0	No	0.0	0.0
90	100	15	0	0	No	4.8	0.0
90	100	15	1	0	No	4.8	0.0
90	100	15	2	0	No	4.8	0.0
90	100	30	0	0	No	4.4	0.0
90	100	30	1	0	No	4.4	0.0
90	100	30	2	0	No	4.4	0.0
90	100	60	0	0	No	1.2	0.0
90	100	60	1	0	No	1.2	0.0
90	100	60	2	0	No	1.2	0.0
90	250	15	0	0	No	0.0	0.0
90	250	15	1	0	No	0.0	0.0
90	250	15	2	0	No	0.0	0.0
90	250	30	0	0	No	0.0	0.0
90	250	30	1	0	No	0.0	0.0
90	250	30	2	0	No	0.0	0.0
90	250	60	0	0	No	0.0	0.0
90	250	60	1	0	No	0.0	0.0
90	250	60	2	0	No	0.0	0.0
90	500	15	0	0	No	0.0	0.0
90	500	15	1	0	No	0.0	0.0
90	500	15	2	0	No	0.0	0.0
90	500	30	0	0	No	0.0	0.0
90	500	30	1	0	No	0.0	0.0
90	500	30	2	0	No	0.0	0.0
90	500	60	0	0	No	0.0	0.0
90	500	60	1	0	No	0.0	0.0

SYSTEM THRESHOLDS						SYSTEM PERFORMANCE	
Pedal Position (%)	**Stroke Rate (%/*s*)**	**Vehicle Speed (*kph*)**	**Recent Braking (*s*)**	**Grade (%)**	**Turning**	**Activated (%)**	**Crashes Avoided (%)**
90	500	60	2	0	No	0.0	0.0

Figure 83 plots the activation rate of these conservative-threshold simulations against their vehicle speed, recent braking, and pedal position thresholds. The number of cases in which the system activated decreased as these thresholds increased. There was no activation among simulations with either 250%/s or 500%/s stroke rate thresholds.

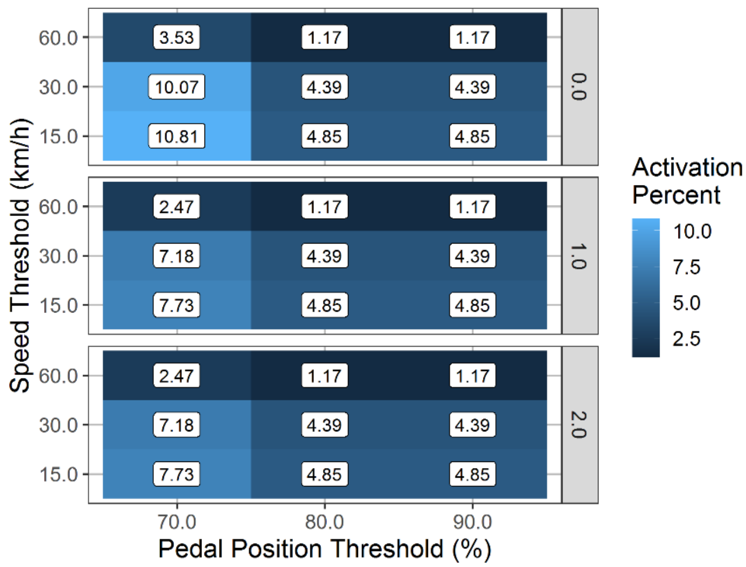

Figure 83. Activation rate organized by vehicle speed threshold (left), recent braking threshold (right), and pedal position threshold (bottom) among conservative-threshold simulations with a stroke rate threshold of 100%/s.

Table 15 displays the same performance metrics among the simulations with combinations of less-conservative thresholds. Among these simulations, activation rate peaked at nearly 30% and crash avoidance at 1.5%. Still, no crashes were avoided with vehicle speed thresholds of 30 kph, stroke rate thresholds of 250%/s or greater, or pedal position thresholds of 50% or greater.

Table 15. Percent of weighted cases in which the accelerator suppression system activated for less-conservative threshold combinations. Grade and turning values were not time-dependent and were based on NMVCCS data.

SYSTEM THRESHOLDS						SYSTEM PERFORMANCE	
Pedal Position (%)	**Stroke Rate (%/*s*)**	**Vehicle Speed (*kph*)**	**Recent Braking (*s*)**	**Grade (%)**	**Turning**	**Activated (%)**	**Crashes Avoided (%)**
0	10	0	0.5	0	No	28.9	1.5

SYSTEM THRESHOLDS						SYSTEM PERFORMANCE	
Pedal Position (%)	**Stroke Rate (%/*s*)**	**Vehicle Speed (*kph*)**	**Recent Braking (*s*)**	**Grade (%)**	**Turning**	**Activated (%)**	**Crashes Avoided (%)**
0	10	30	0.5	0	No	26.0	0.0
0	25	0	0.5	0	No	28.9	1.5
0	25	30	0.5	0	No	26.0	0.0
0	50	0	0.5	0	No	28.9	1.1
0	50	30	0.5	0	No	26.0	0.0
0	75	0	0.5	0	No	23.1	0.8
0	75	30	0.5	0	No	20.5	0.0
0	100	0	0.5	0	No	20.0	0.4
0	100	30	0.5	0	No	17.9	0.0
0	250	0	0.5	0	No	0.0	0.0
0	250	30	0.5	0	No	0.0	0.0
0	500	0	0.5	0	No	0.0	0.0
0	500	30	0.5	0	No	0.0	0.0
25	10	0	0.5	0	No	22.9	0.3
25	10	30	0.5	0	No	20.8	0.0
25	25	0	0.5	0	No	22.9	0.2
25	25	30	0.5	0	No	20.8	0.0
25	50	0	0.5	0	No	22.9	0.2
25	50	30	0.5	0	No	20.8	0.0
25	75	0	0.5	0	No	20.0	0.2
25	75	30	0.5	0	No	17.9	0.0
25	100	0	0.5	0	No	20.0	0.2
25	100	30	0.5	0	No	17.9	0.0
25	250	0	0.5	0	No	0.0	0.0
25	250	30	0.5	0	No	0.0	0.0
25	500	0	0.5	0	No	0.0	0.0
25	500	30	0.5	0	No	0.0	0.0
50	10	0	0.5	0	No	7.7	0.0
50	10	30	0.5	0	No	7.2	0.0
50	25	0	0.5	0	No	7.7	0.0
50	25	30	0.5	0	No	7.2	0.0
50	50	0	0.5	0	No	7.7	0.0
50	50	30	0.5	0	No	7.2	0.0
50	75	0	0.5	0	No	7.7	0.0
50	75	30	0.5	0	No	7.2	0.0
50	100	0	0.5	0	No	7.7	0.0
50	100	30	0.5	0	No	7.2	0.0
50	250	0	0.5	0	No	0.0	0.0
50	250	30	0.5	0	No	0.0	0.0
50	500	0	0.5	0	No	0.0	0.0
50	500	30	0.5	0	No	0.0	0.0
75	10	0	0.5	0	No	7.7	0.0

SYSTEM THRESHOLDS						SYSTEM PERFORMANCE	
Pedal Position (%)	**Stroke Rate (%/*s*)**	**Vehicle Speed (*kph*)**	**Recent Braking (*s*)**	**Grade (%)**	**Turning**	**Activated (%)**	**Crashes Avoided (%)**
75	10	30	0.5	0	No	7.2	0.0
75	25	0	0.5	0	No	7.7	0.0
75	25	30	0.5	0	No	7.2	0.0
75	50	0	0.5	0	No	4.8	0.0
75	50	30	0.5	0	No	4.6	0.0
75	75	0	0.5	0	No	4.8	0.0
75	75	30	0.5	0	No	4.6	0.0
75	100	0	0.5	0	No	4.8	0.0
75	100	30	0.5	0	No	4.6	0.0
75	250	0	0.5	0	No	0.0	0.0
75	250	30	0.5	0	No	0.0	0.0
75	500	0	0.5	0	No	0.0	0.0
75	500	30	0.5	0	No	0.0	0.0

For these less-conservative thresholds, the effects of the stroke rate and pedal position thresholds on the system's crash avoidance performance were investigated further in Figure 84. Although more susceptible to false activation, less-conservative thresholds resulted in more crashes avoided as compared to more-conservative thresholds. It was noteworthy that, although there were no activations or crashes avoided with a stroke rate of 250%/s, there were three SHRP 2 NDS pedal profiles which reached a stroke rate of greater than or equal to 250%/s. However, all three profiles reached this stroke rate between the last two measured accelerator pedal positions, i.e., at the time of the crash. Therefore, the system did not have time to activate, even if all of the other activation conditions were met. Even if activated, the system would not have had enough time to substantively improve the crash outcome. None of the pedal profiles reached a stroke rate of 500%/s. Additionally, the effects of the stoke rate and pedal position thresholds on the system's activation were investigated in Figure 85. The percentage of simulations resulting in system activation were substantially higher for pedal position thresholds of 0.0% and 25.0% in comparison to the 50.0% and 75.0% thresholds.

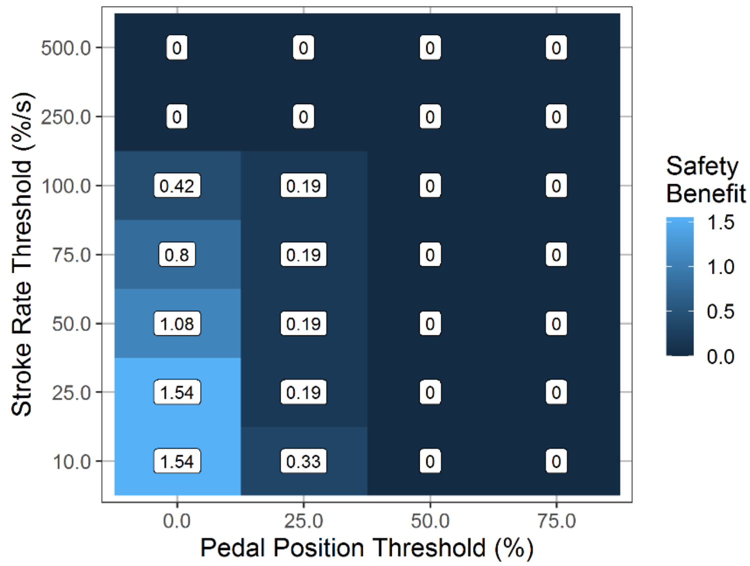

Figure 84. Crash avoidance among simulations by pedal position threshold and stroke rate threshold. The value in each region represents the percentage of simulations that resulted in an avoided crash.

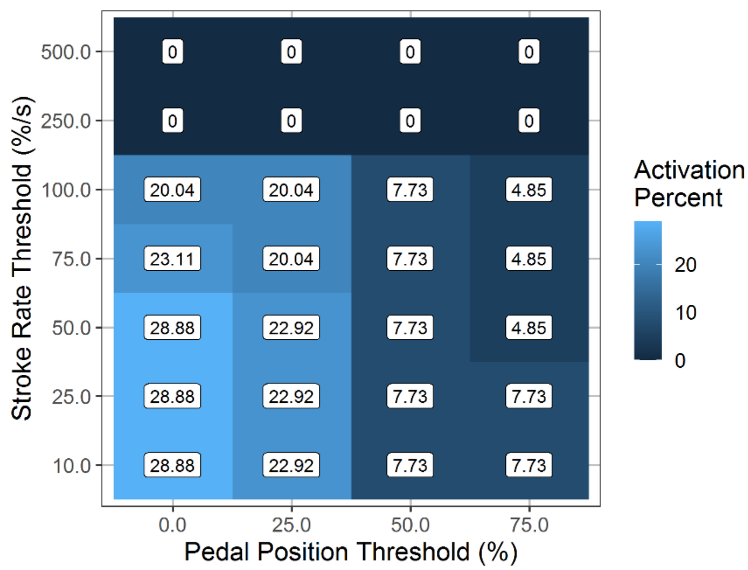

Figure 85. System activation among simulations by pedal position threshold and stroke rate threshold. The value in each region represents the percentage of simulations resulting in system activation.

The crash avoidance of the system given that it was activated and irrespective of system thresholds is plotted in Figure 86 as a cumulative distribution of PM speed. Crashes that the system was able to prevent (green) generally had lower speeds (< 7 m/s, or 15.7 mph) at the time of PM.

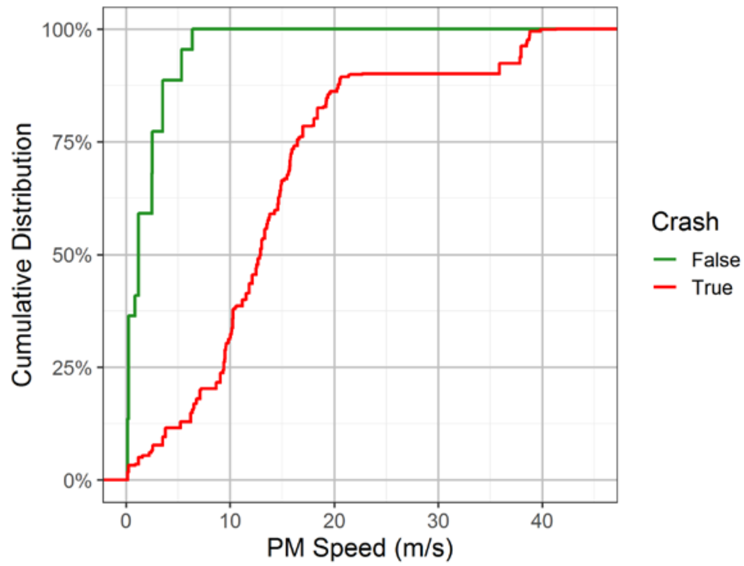

Figure 86. Crash outcome as a cumulative distribution function of PM speed among cases in which the accelerator suppression system was activated.

The crash status was investigated for residual system-activated crashes. Figure 87 presents the crash status as a function of vehicle position relative to the collision and vehicle speed at the time of PM for activated cases in which the vehicle crashed. For crashes that occurred later than originally simulated, the crash was delayed by an average of 0.57 s. The TTC at the point of PM is defined as the ratio of the distance to impact (PM position) to the PM speed. The black line on the plot represents a TTC of 1.67 s, and nearly all crashes that were delayed by the acceleration suppression system had TTCs greater than this value, although not all crashes with TTCs greater than this value were delayed. This is partly because the time of activation is not necessarily equal to the time of PM and depends on the activation thresholds. While the TTC may be large at the time of PM, it may be very small at the time of activation, and the longer the activation is delayed, the less likely the system will be able to have a substantial effect on the crash time or speed. The trend becomes clearer when focusing on a single combination of low activation thresholds (Figure 88), where the probability that the system activated at the time of PM is relatively large. Still, conditions (e.g., recent braking) may prevent the system from activating at the time of PM, and cause the system to have an insignificant effect on crashes – even crashes with large TTCs at the time of PM. Further, even when other conditions do not prevent the activation at the earliest time of PM, there are still crashes with large TTCs that are not delayed. This is because the effect of engine power on the vehicle speed is inversely proportional to the vehicle speed. In other words, at very high speeds, the accelerator input becomes less influential to the vehicle acceleration. Suppression at very high speeds, therefore, had less of an effect on vehicle speed throughout these simulations and, as a result, crash time was not significantly reduced (represented by the blue dots on right of Figure 88 corresponding to vehicle speeds of approximately 80 mph).

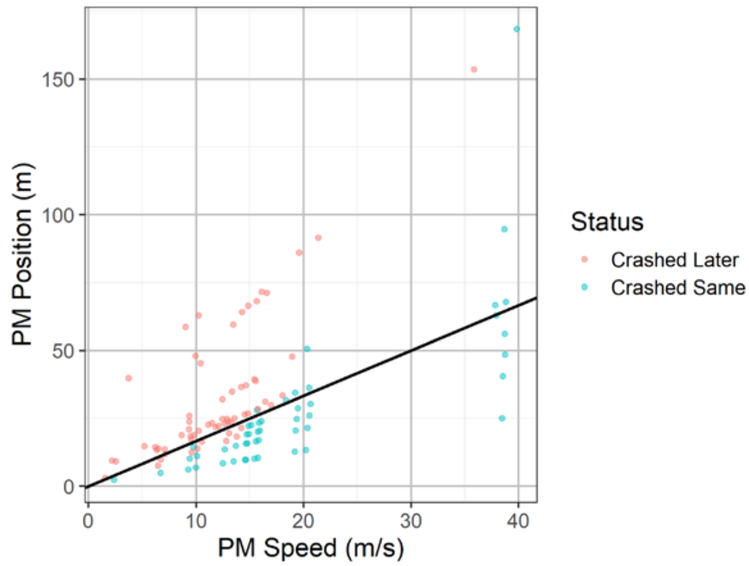

Figure 87. Crash status as a function of PM position and PM speed among cases in which the accelerator suppression system was activated and the vehicle crashed for all threshold combinations.

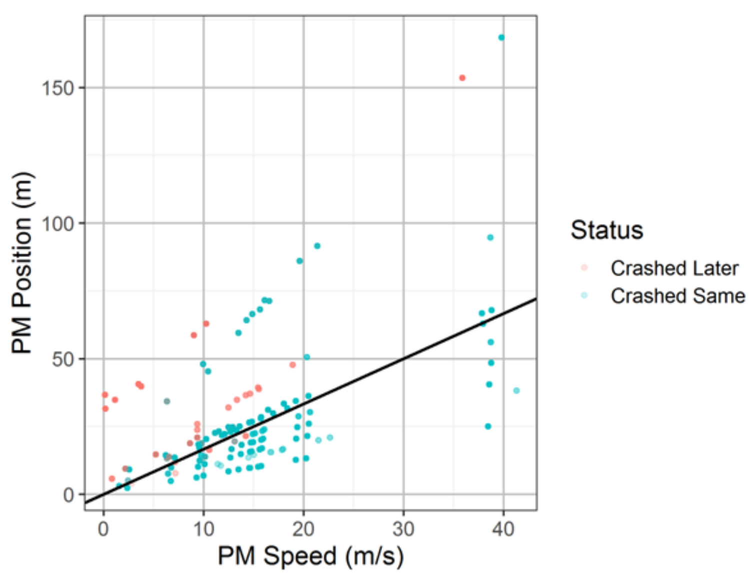

Figure 88. Crash status as a function of PM position and PM speed among cases in which the accelerator suppression system was activated and the vehicle crashed (system thresholds: pedal position = 0%, stroke rate = 25%/s, vehicle speed = 0, recent braking = 0.5 s, grade = 0%, turning = No.

Because few crashes were prevented, system-activated cases were also analyzed for speed reduction. Figure 89 and Figure 90 present cumulative distribution functions of impact speed reduction in units of percent and speed for all threshold combinations. Impact speed reduction was calculated as the difference in impact speed in the activated case relative to the original crash. These figures include cases in which the crash was avoided, which are represented by a 100% speed reduction. The median system-activated case had a speed reduction of about 9% or 3.1 mph (5 kph).

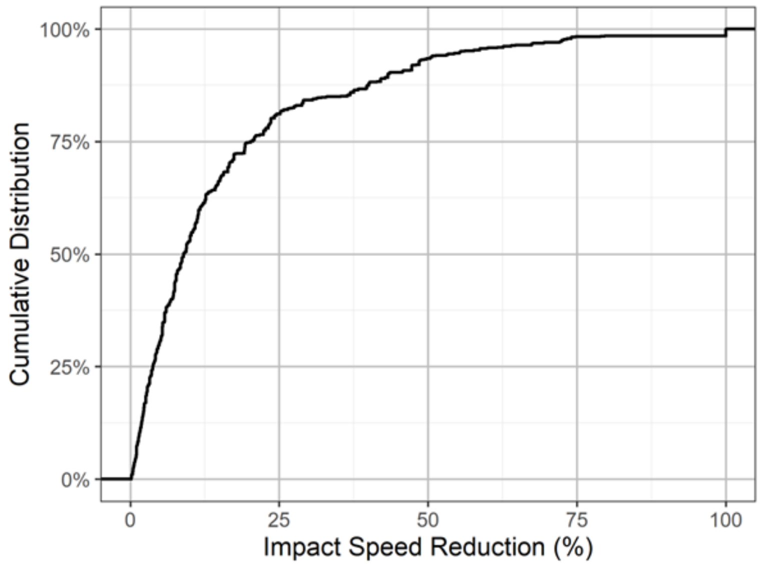

Figure 89. Cumulative distribution function of the percent of vehicle's original impact speed that was reduced by the acceleration suppression system for all cases in which the system activated.

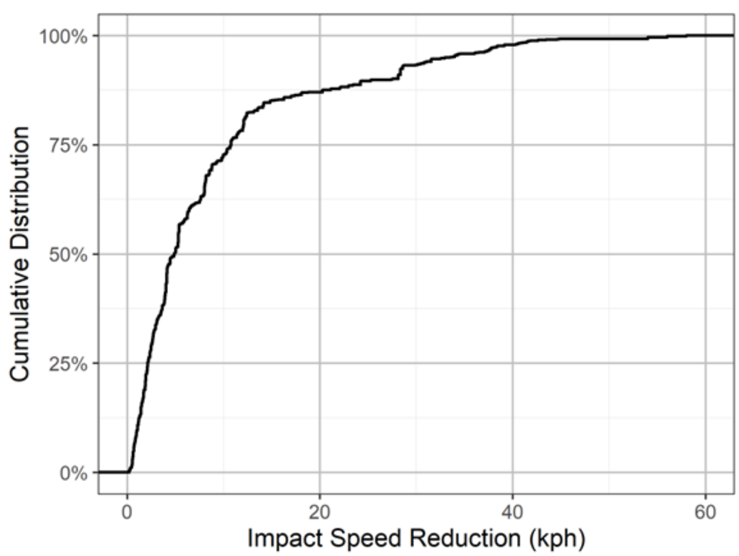

Figure 90. Cumulative distribution function of the impact speed reduction (kph) caused by the acceleration suppression system for all cases in which the system activated.

Figure 91 illustrates the estimated crash avoidance potential of the acceleration suppression system in combination with braking for all cases in which the system activated, regardless of whether the crash was prevented with accelerator suppression alone. This supplemental analysis assumed that braking was applied at the same time as system activation with a jerk of 11 m/s^3 up to a maximum deceleration of 0.6 g. After applying NMVCCS case weights, 24.7% of cases had the potential to be avoided with brake application.

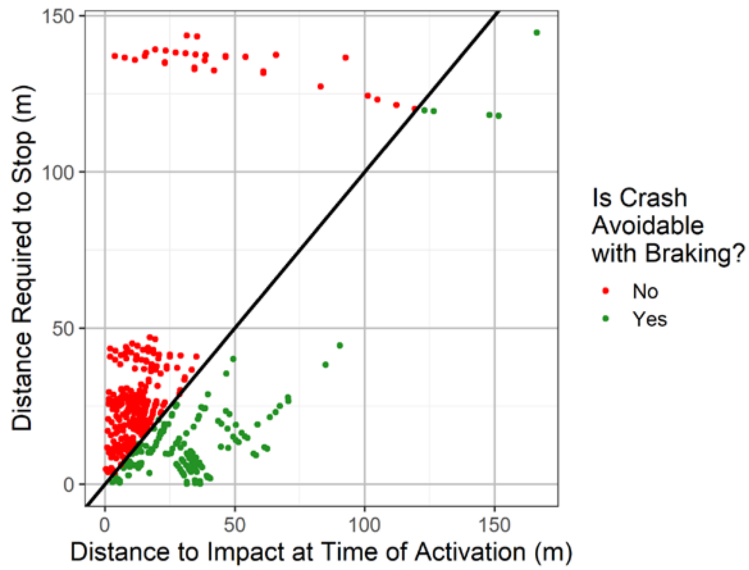

Figure 91. Scatterplot of the approximated distance required for the vehicle to come to a stop versus the distance to the impact at the time of system activation for all cases in which the system activated regardless of whether the crash was prevented by accelerator suppression alone. Points beneath the line represent cases that could be avoided with braking.

Similar to analysis of the accelerator suppression speed reduction, the speed reduction of acceleration suppression in combination with braking was analyzed. In Figure 92, the 24.7% of system-activated crashes that were avoidable with accelerator suppression and braking established in Figure 93 are represented by a 100% speed reduction. The median speed reduction in these cases is about 25% or 10.6 mph (17 kph).

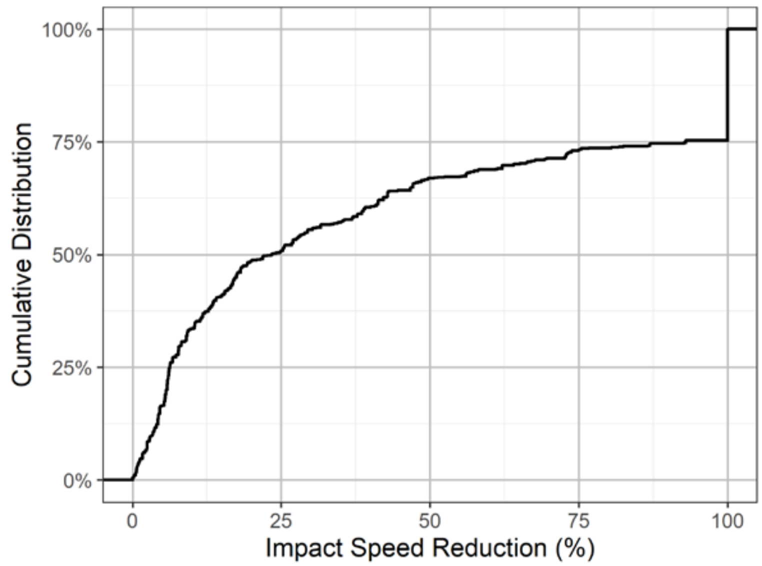

Figure 92. Cumulative distribution function of the percent of vehicle's original impact speed that was reduced by the acceleration suppression system with braking for cases in which the system activated.

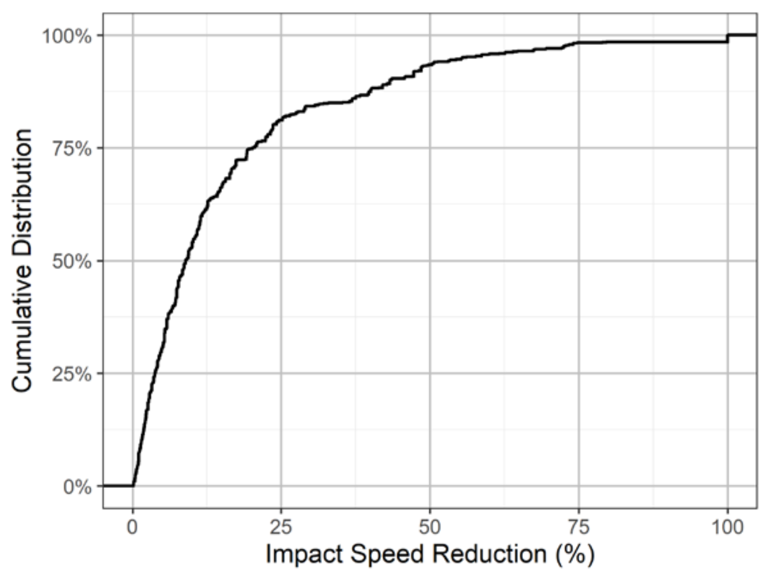

Figure 93. Cumulative distribution function of the impact speed reduction (kph) caused by the acceleration suppression system with braking for cases in which the system activated.

6.5 Discussion

In this study, a dynamic simulation was developed and informed with real-world, confirmed PM crash data from the NMVCCS and SHRP 2 NDS databases. A theoretical accelerator suppression system was implemented into the simulation and tested with a variety of condition thresholds. The simulated accelerator suppression system was largely ineffective at preventing these PM crashes. Even with the least conservative activation thresholds simulated, crash avoidance never surpassed 2% and system activation never exceeded 30%. This failure to prevent crashes is primarily attributed to the absence of incorporated braking into the system and the range of selected system thresholds. The effect of braking was analyzed, and it was estimated that the PM crash could be avoided in nearly a quarter of system-activated cases. Impact speeds were significantly reduced (by more than 60 mph or 97 kph in some cases) as compared to acceleration suppression alone.

The activation rates found in this study are dependent on the selected system thresholds. More-conservative thresholds (e.g., higher pedal positions, higher stroke rates, higher vehicle speeds, longer recent braking time periods) result in lower activation rates, lower speed reductions, and fewer crashes prevented. Meanwhile, the converse is also true: less-conservative thresholds result in greater safety benefit. Of course, less-conservative thresholds are also conceivably correlated with higher rates of inappropriate system activation during non-PM scenarios. Although this study only simulated crashes with confirmed PMs, the activation of this system in non-PM crashes could be quantified based on the SHRP 2 NDS analysis in Chapter 5 (Figure 94). Among all crashes in SHRP 2 NDS, approximately 25% involved a stroke rate greater than 50%/s but only approximately 10% involved a stroke rate greater than 100%/s.

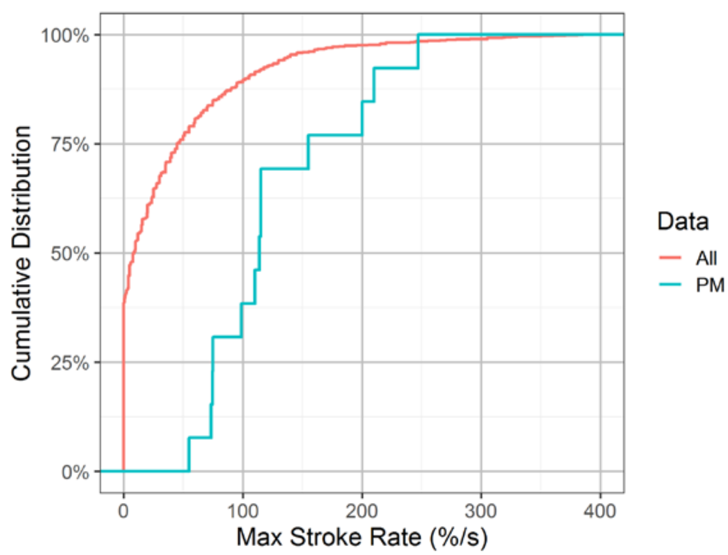

Figure 94. Cumulative distribution functions of maximum stroke rate (accelerator pedal application rate) for all crashes and manually confirmed PM crashes from SHRP2. Maximum stroke rate can be greater than 100%/s because the sampling rate is less than one second.

Figure 95 analyzes this trend across all simulated pedal position thresholds to estimate the potential for inappropriate system activation. The SHRP 2 NDS crash data was used to estimate the proportion of all crashes the accelerator suppression system would activate for a given accelerator pedal threshold and stroke rate threshold combination. An accelerator suppression system with a stroke rate threshold of 100%/s would activate in less than 13.5% of SHRP 2 NDS crashes (Figure 95). However, the system which activated at an accelerator position of at least 75% and a stroke rate threshold between 25%/s and 50%/s had the highest precision (Figure 96). In other words, that system configuration had the highest proportion of PM crashes present among the crashes for which it activated.

Combinations with a stroke rate threshold over 250 %/s or a pedal position threshold over 50% had significantly fewer false activations than those below both of those thresholds (Figure 97).

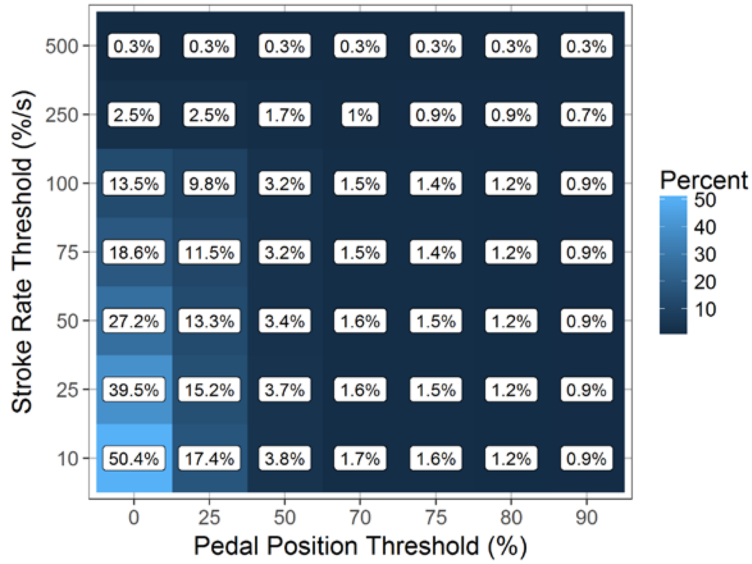

Figure 95. The percent of all SHRP 2 NDS crashes that satisfy the given stroke rate and pedal position thresholds.

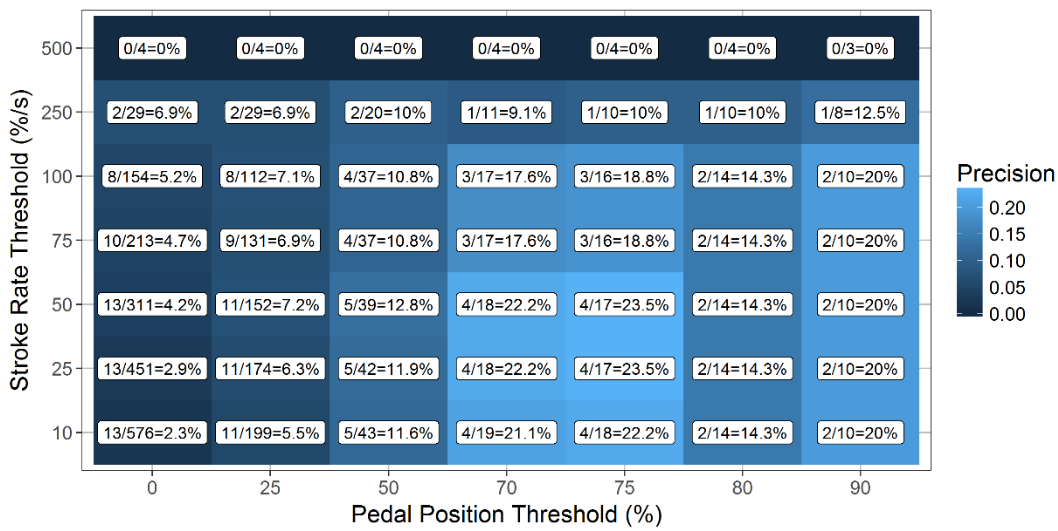

Figure 96. The precision of the accelerator suppression system based on the SHRP 2 NDS crash data.

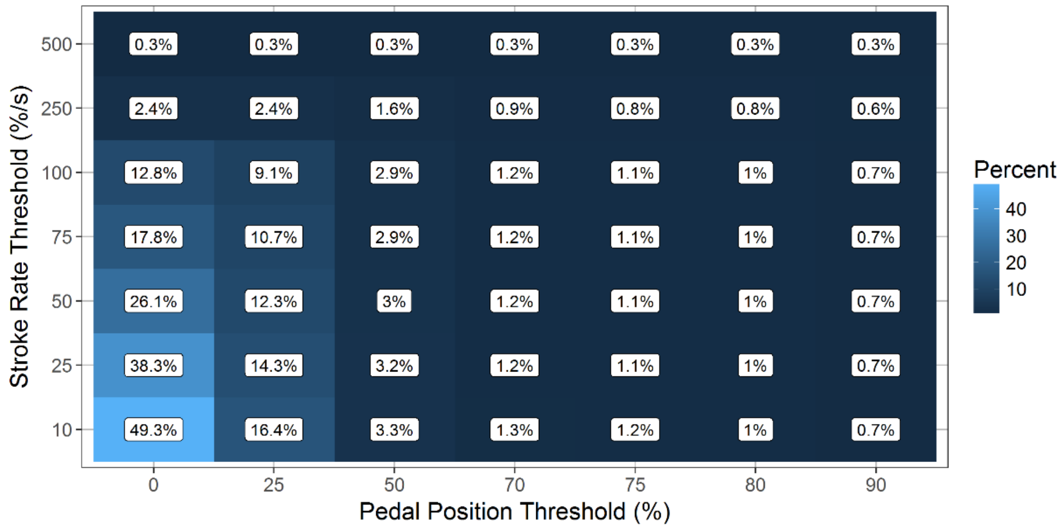

Figure 97. The percent of false activations among all SHRP 2 NDS crashes for a given stroke rate and accelerator position threshold combination.

6.5.1 Limitations

The simulated vehicle dynamics were simplified by assuming the engine power output was linearly proportional to the accelerator pedal position. Generally, more power is generated from 0% to 10% accelerator application than from 90% to 100% in what is colloquially known as the “test drive effect”. The accelerator pedal position-engine power relationship is variable among vehicles and highly dependent on the proprietary design of the throttle control system. In this study, it was not feasible to account for this, suggesting that the simulation may underestimate accelerations resulting from PMs at low pedal positions and overestimate those at high pedal positions. Additionally, driver braking input was assumed to take a maximum deceleration of 0.4 g. While greater than typical braking deceleration of natural driving, this is a conservative approximation for emergency braking, which depends on the vehicle and the environment and can be significantly higher. Along these lines, the supplemental analysis that evaluated the potential system performance if braking was activated at the moment of accelerator suppression applied a maximum deceleration of 0.6 g. Some current AEB systems are capable of applying emergency braking decelerations of greater than 1.2 g.[110] These limitations suggest that the calculated potential safety benefit of the simulated system may be a conservative estimate and the actual safety benefit could be higher.

The simulation modeled the vehicle on a predetermined path that intersected a static object. If the vehicle traveled the distance required to collide with the static object, it was considered to have crashed. Steering input and the dynamics of the impacted object were not considered. Additionally, the simulation did not consider the reaction of the driver to the activation of the acceleration suppression system, e.g., corrective braking. The braking behavior in the system-activated simulations remained the same as the braking behavior in the original pedal profile. Since system-activated scenarios could last longer than the original crashes, braking status after the original crash time was assumed to stay constant.

This limits the results to the extent that the driver would have changed their braking behavior when presented with system activation and suggests that the results underestimate the prevalence of avoidable crashes.

Regarding the accelerator suppression system conditions, each condition was evaluated at each time point. However, due to data availability, grade and turning status were determined based on the NMVCCS case and were not time-dependent. If a vehicle appeared to be turning based on the crash scene diagram, the vehicle was assumed to have had its turn signal activated for the entire duration of the simulation, and each simulation involving that NMVCCS case was never eligible for system activation. Similarly, if NMVCCS reported the grade to be positive, the grade was assumed to be positive for the entire duration of the simulation, and each simulation involving that NMVCCS case was never eligible for system activation. Either of these conditions prevented the system from activating in 12 out of 22 of the NMVCCS cases (12 cases turning and two cases travelling uphill with both cases traveling uphill also turning), corresponding to approximately 55% of all simulations.

The ability to generalize these results to the larger PM crash population is limited because the samples are small. Only 22 NMVCCS cases were combined with 13 SHRP 2 NDS pedal profiles to simulate a larger variety of crashes. While the SHRP 2 NDS pedal profiles are not from the NMVCCS crash and may not capture context-depended nuances of PM pedal application, they were imposed onto the NMVCCS crashes to represent many of the possible PM pedal profiles that could have occurred. Each PM crash is unique, and the combination of these few crashes and pedal profiles does not represent every PM crash.

6.6 Conclusions

A theoretical acceleration suppression system was applied to data from confirmed PM crashes to simulate vehicle dynamics and estimate safety benefit. Because of activation requirements, the accelerator suppression system did not activate in the majority of PMs, and the crash occurred as originally modelled. The simulation results indicated that acceleration suppression alone proved insufficient to prevent crashes and had only a small effect on impact speed reduction. Less-conservative system condition thresholds resulted in higher rates of activation and crash avoidance. Acceleration suppression in combination with braking, however, proved most promising with substantial rates of crash avoidance and significant impact speed reduction. Yet, even with braking, some crashes proved unavoidable. The vehicles in these residual crashes were traveling at excessive speeds at the time of activation and did not have enough distance to stop prior to impact.

Chapter 7: Conclusion

The purpose of the studies described in Chapters 3, 4, and 5 was to analyze databases with established and novel methods to augment past research on PM crash frequency and characterization. This was accomplished using the NC state crash database, NMVCCS, NASS/CDS, and SHRP 2 NDS. Similar to previous work, a keyword search across crash narratives was used to identify PM crashes the NC state and NMVCCS databases. Using the time-series pre-crash accelerator pedal information recorded by the EDR, PM-like crashes were identified in NASS/CDS. A similar pedal position method was used to identify potential PM crashes in SHRP 2 NDS, but forward facing and driver facing videos provided researchers with the ability to confirm PM crashes. A comparison between the results from each of these datasets is discussed below (Table 16).

- *PM Crash Frequency.* The estimated frequency of PM crashes among the eligible crashes was very similar in the NC state crash data (0.18%) and the NMVCCS data (0.22%). The number of PM-like crashes was much higher at 4.3% in the NASS/CDS dataset, though PM crashes could not be distinguished from PM-like pedal behavior. The PM crash rate was calculated as 1.1% in the SHRP 2 NDS dataset.
- *Driver Sex*. Similar to previous work, drivers that commit PMs resulting in a crash were more likely to be female in the NC state crash database, NMVCCS, and SHRP 2 NDS datasets. In NASS/CDS, male drivers were more frequently involved in the PM-like crashes. This could be due to a variety of factors, including the presence of aggressive driving behaviors identified as PM-like pedal behaviors.
- *Driver Age*. Among the datasets, the oldest and – to lesser degree – youngest drivers appeared to be more likely to commit a PM that results in a crash. Within the SHRP 2 NDS dataset, nearly 70% of the PM drivers were over the age of 65 years. This is in part because SHRP 2 NDS intentionally oversampled older drivers. In the NC state crash database, drivers of the same age range constituted approximately 30% of PM crashes versus approximately 16% of all crashes.
- *Pedal Behavior.* Pedal data was only available for PM crashes in SHRP 2 NDS and PM like crashes in NASS/CDS with EDRs. Pedal switching was observed in both datasets with the median driver changing pedal engagement once approximately every two seconds. In SHRP 2 NDS, the accelerator pedal reached over 99% in 15% of PM crashes and both the brake and accelerator were activated simultaneously in 27% of PM crashes.

Table 16. Summary of PM crash characterizations from the four analyzed crash datasets.

Dataset		NC State	NMVCCS (unweighted)	NASS EDR (unweighted)	SHRP 2
Chapter		3	3	4	5
Population		1,869,886	2,188,970 (6,949)	770,628 (1,525)	1,143
Identification Method		Keyword Search	Keyword Search	Pedal Position (PM-Like)	Pedal Position + Video
PM Crashes		3,274	4,859 (33)	32,882 (77)	13
PM Frequency		0.2%	0.2% (0.5%)	4.3% (5.0%)	1.1%
Pedal Flooring		-	-	27.3%	15.4%
Both Brake and Accelerator Active		-	-	11.4%	27.3%
Median Speed at PM (mph)		-	-	46.0	3.5
Driver Age (years)	Under 25	19.3%	34.5%	36.6%	7.7%
	25 to 65	50.7%	43.5%	53.0%	23.0%
	Over 65	27.3%	22.0%	10.4%	69.3%
Driver Sex	Male	47.1%	36.2%	60.2%	46.2%
	Female	52.9%	63.8%	39.8%	53.8%
Pedal Switch Rate (switches/s)	25th	-	-	0.25	0.21
	50th	-	-	0.5	0.63
	75th	-	-	0.8	0.83
Stroke Rate (%/s)	25th	-	-	37	75
	50th	-	-	64	114
	75th	-	-	96	247
Stroke (%)	25th	-	-	34	37.5
	50th	-	-	58	47.8
	75th	-	-	100	76

The databases of these analyses were chosen to some extent for the purpose of comparison with one another. Ultimately, however, the samples obtained from these databases represent different populations as determined by the identification methodologies and the database's study design, including their crash inclusion criteria. The 3,274 crashes from the NC state crash databases represent a population of police-reported crashes in the state of NC between the years of 2014 and 2020 that contained a certain combination of letters in the narrative. This is a wildly different population than that of tow-away crashes on public roads across the United States from 1997 to 2015 with evidence of PM contained in EDRs being represented by the 77 NASS/CDS crashes. All of the elements that influence the makeup of the investigated samples need to be evaluated as we approach a more informed estimate of the true frequency and characteristics of PM crashes. Despite these differences, one thing is clear: **the prevalence of PM crashes is likely to be higher than previously thought**.

The purpose of the study described in Chapter 6 was to evaluate the potential safety benefit of a theoretical PM crash mitigation and prevention ADAS. Using real-world, confirmed PM crash data, including the pedal profiles from SHRP 2 NDS and crash data from NMVCCS, the PM crashes were simulated with the application of various configurations of an accelerator suppression system. The pedal profiles from SHRP 2 NDS were also used to understand system activation dynamics in PM crashes and non-PM crashes for each combination of stroke rate and accelerator position thresholds. The precision, or proportion of system activations during a PM crash among all system activations, was used to understand the trade off with false activations.

Because the system only suppressed the accelerator input and did not apply any braking, very few crashes were prevented. In all simulated accelerator suppression system threshold combinations, the crash avoidance did not surpass 1.54%. For systems with higher pedal position thresholds, the accelerator suppression system only activated in a few cases and was unable to avoid any crashes. However, the accelerator suppression system did reduce the median impact speed by 3.1 mph. The highest activation precision occurred for a system with a 75% accelerator position threshold and a stroke rate threshold between 25%/s and 50%/s. However, at those thresholds, no crashes were prevented with accelerator suppression alone. Future systems could include automatic braking to substantially improve the benefit among PM crashes.

Future Work

There is always room for advancement in the identification and characterization of PM crashes. As databases collect more robust data from crashes, there may be opportunity to validate PM crashes identified through EDR or other methods in large scale databases like NASS/CDS, such as its successor, the Crash Investigative Sampling System. This could allow for better evaluation and optimization of the EDR identification method that was not afforded by SHRP 2 NDS sample due to the small sample size and low-severity nature of the PM crashes identified.

Next steps resulting from the study described in Chapter 6 include improving the accuracy of the model. This can be done in a number of ways, such as inputting an accurate and representative transfer function converting accelerator pedal position to engine power, which would result in improved speed predictions. Also, because the impacted objects in simulated PM scenarios were assumed to be fixed and the PM vehicle was assumed to travel only on a path which intersected the impacted object, neither the dynamics of the impacted objected nor steering evasive maneuvers of the PM driver were incorporated. These additions could lead to higher and more accurate safety benefit estimates.

Beyond modeling, it would be insightful to further develop this technology to a prototype stage that would allow for human subject testing. The six activation requirements of the modeled system are easily measured, and the data required is readily available in many modern vehicles that already sample accelerator pedal position. Human subject testing could elucidate more data on the probability of false activation and provide more naturalistic data to refine and optimize the activation requirement thresholds, bringing this technology closer to deployment.

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Appendix

Table 17. Number of observations for each factor analyzed in the NC state crash database.

Table	Factor	Description	All	PM
Accident	ALC_INVLV	Alcohol Involved	1,678,318	3,088
Accident	CRASH_DATE	Crash Calendar Date	1,647,859	3,088
Accident	CRASH_DATE	Crash Weekday	1,678,318	3,088
Accident	SEVERITY	Injury Severity	1,628,539	3,060
Accident	FRST_HMFL_TXT	First Harmful Event at Crash Level	1,676,499	3,088
Accident	WTHR_TXT	Weather Condition	1,678,318	3,088
Accident	DEV_TXT	Predominant Development Type	1,678,318	3,088
Accident	SPDLMT	Authorized Speed Limit	1,644,628	2,966
Accident	DMG_AMT	Damage Amount	1,669,247	3,077
Vehicle	VEHTYPE_TXT	Vehicle Type	2,972,452	3,016
Vehicle	DRIVER_AGE	Age of Driver	2,829,464	3,008
Vehicle	EST_SPEED	Estimated Speed Prior to Impact	2,835,163	2,885
Person	GENDER	Gender	2,824,673	3,016

Table 18. Number of observations for each factor analyzed in NMVCCS.

Table	Factor	Description	All	PM
CRASH	TIME	Time of Day	5,470	26
CRASH	INJSEVA	Max. Injury Severity	5,279	26
CRASH	DAYWEEK	Weekday	5,470	26
CV	BACTEST	BAC Test Result	9,841	25
CV	DLSTATUS	Driver’s License Status	9,605	25
CV	TRSPEED	Travel Speed	9,449	24
ENV	SPLIMIT	Speed Limit	10,033	26
OCC	AGEYEAR	Age	10,035	26
OCC	HEIGHT	Height	7,894	22
OCC	SEX	Sex	10,127	26
PCA	ACCTYPE	Accident Type	10,080	26
PCA	FATIGUE	Fatigue	7,692	20
PCA	INATTEN	Inattention	7,971	22
PCA	WEATHER	Weather	5,466	26
GV	BODYTYPE	Vehicle Body Type	10,494	26

Table 19. Number of observations for each factor analyzed in NASS/CDS.

	Weighted Crashes		Case Weights	
Factor	All	PM	All	PM
Alcohol Involved	68,883	68	38,257,454	28,901.39

Factor	Weighted Crashes All	Weighted Crashes PM	Case Weights All	Case Weights PM
Drugs Involved	60,062	61	34,662,325	26,706.34
Crash Time	82,339	76	43,366,265	31,335.06
Crash Weekday	82,755	77	43,623,355	32,882.07
Police Reported Travel Speed	48,849	28	34,542,065	12,809.69
Weather	146,272	77	77,865,270	32,882.07
Posted Speed Limit	145,200	77	77,460,716	32,882.07
Vehicle Body Type	148,831	77	78,847,819	32,882.07
Driver Distracted	66,032	37	36,633,986	17,514.44
Driver Fatigue	66,032	37	36,633,986	17,514.44
Age	116,327	75	55,054,285	29,104.05
Sex	116,968	75	55,404,520	29,104.05
Height	84,281	62	39,358,311	23,871.72
KABCO Injury Severity	81,333	71	42,548,915	27,095.86

Table 20. Number of observations for each factor analyzed in SHRP 2 NDS.

Factor	Crashes All	Crashes PM
Alcohol Involved	1835	13
Drugs Involved	1835	13
Travel Speed	1127	13
Weather	1836	13
Locality	1836	13
Vehicle Body Classification	1826	13
Driver Distracted	1826	13
Driver Fatigue	1835	13
Driver Age	1816	13
Driver Sex	1826	13