THE FUTURE OF TRANSPORT

PUBLISHED PROJECT REPORT PPR2015

Pedal Misapplication Study

Karthikeyan Ekambaram, Bethany Frox, Niamh Bull, Emma Lyndon, Hannah Wright

Report details

Report prepared for:	Department for Transport, International Vehicle Standards		
Project/customer reference:	TETI1021C		
Copyright:	© TRL Limited		
Report date:	10/05/2023		
Report status/version:	v1.0		
Quality approval:			
Ashleigh Osborne-Scott (Project Manager)	04/04/2023	David Hynd (Technical Reviewer)	17/05/2023

Disclaimer

Executive Summary

This study examined the characteristics of collisions related to pedal misapplication. Specific goals were to examine the role of the driver, vehicle, roadway, and environmental characteristics; and the extent of injury severities caused by these errors.

A systematic literature review was performed to explore the topic of pedal misapplication. Eighteen academic papers and ten related media articles were identified through a systematic selection process for review. Previous research has demonstrated that pedal misapplication occurs not only during initial start-up and low-speed parking manoeuvres, but also throughout the entire driving cycle. Pedal misapplication occurs across all driver groups; however, previous studies have associated pedal misapplication collisions with certain risk factors such as old age, cognitive impairment, small stepover pedal configuration, incorrect foot positioning, hesitant braking, short stature, smaller shoe size and possibly being female. The review has also presented countermeasures, including technologies that are available in the market, which have the potential to mitigate collisions caused by pedal misapplication.

Real-world collision data from the Road Accident In-Depth Studies (RAIDS) database between 2012 and 2023 were interrogated to identify pedal misapplication related collisions for further analysis. RAIDS is the UK's in-depth collision data collection programme, designed to create an evidence base to support improved road safety. The development of appropriate and cost-effective policies, technologies and solutions to prevent future loss of life and injury in road traffic collisions depend entirely on reliable data at the required level of detail to provide a deep understanding of road collisions (vehicle, user and environment) and the mechanisms which result in road collisions and injuries.

RAIDS investigations differ from those of the police because they are designed to understand all factors influencing a collision and its outcome rather than necessarily determine responsibility. Typically, the team will investigate around 200 cases per year; these are a mix of investigations carried out at the live collision scene and retrospective investigations based on vehicle examinations and analysis of police collision reports. This information is held in a single comprehensive database which provides an invaluable evidence-based research tool which is used extensively in road safety improvement programmes, medical research, vehicle standards and design. Since the start of RAIDS, over 125 research studies have utilised the RAIDS database for research projects.

Within this study, analysis of the relevant 43 pedal misapplication RAIDS cases showed that most of those collisions were caused by the driver accelerating instead of applying brakes. From the collision sample, a higher proportion of crashes related to pedal misapplication occurred on smaller, lower-class carriageways or private parking spaces with lower speed limits compared to other crashes. The majority of the RAIDS pedal misapplications (about 49%) occurred at the initial start-up of the vehicle. Manoeuvring (mostly related to parking) and cornering were the most coded collision types within the pedal misapplication sample.

Within the sample, elderly drivers and female drivers were more often involved in a pedal misapplication related crash. The most common impairment-related contributing factors in pedal misapplication crashes were driver distraction and illness. Analysis of RAIDS data

shows that the consequences of pedal misapplication crashes are relatively not severe compared to all crashes in the RAIDS database, mainly due to the low initial velocity in most of the pedal misapplication cases.

Within the RAIDS database, vehicles fitted with automatic transmissions are more frequently associated with pedal misapplication cases. Only 3 of the RAIDS pedal misapplication case were hybrid/electric vehicles. However, it is important to consider the predicted rapid uptake of electric vehicles, as those vehicles are mostly fitted with an automatic transmission and typically able to accelerate much faster than the conventional internal combustion engine. This could lead to an increase in pedal misapplication collision, potentially of increasing severity, as the popularity of these vehicles increases.

This study findings provided useful insights about crash characteristics and contributory factors of collisions related to pedal misapplication. Crash mitigation systems are growing in popularity amongst vehicle manufacturers. Encouraging the manufacturers to develop and fit a system that can detect and mitigate pedal misapplication related collisions can be beneficial. This can be achieved through rewarding points in consumer test programmes such as Euro NCAP or through relevant standards that make the fitment of such systems mandatory.

Table of Contents

1 Introduction

Pedal misapplication is when the driver applies the wrong pedal of a vehicle, for example: accelerating instead of braking and braking instead of accelerating. One of the human factors that causes pedal misapplication error includes pedal confusion. Transport for London (TfL, 2022) has described pedal confusion as "the manoeuvre where a driver confuses the acceleration pedal with the brake pedal resulting in either sudden unintended acceleration (SUA) or harsh braking". It should be noted that pedal misapplication is not synonymous with pedal confusion, rather a potential outcome of pedal confusion. Unfortunately, pedal misapplication followed by the inability to regain control of the vehicle can result in collisions. These collisions can cause damage to vehicles and surrounding infrastructure and can result in the fatal injury of nearby pedestrians. Research has highlighted the prevalence of this issue by analysing crash data and attempting to identify the proportion caused by pedal confusion. According to the National Highway Traffic Safety Administration (NHTSA) there are approximately 16,000 collisions that occur per year due to pedal misapplication in the US (NHTSA, 2015). As for the UK, TfL has identified 244 pedal confusion incidents and 75 injuries involving buses for the period April 2010 to January 2022[1]. There is speculation that both figures are an underestimate of the number of crashes that result from pedal confusion because understanding the cause of collisions relies heavily on driver statements, which are unreliable as they often claim to have been pressing the correct pedal. As a result, investigators are reliant on other data sources (e.g., camera footage, checking the vehicle controls were operating correctly) to determine the cause of the collision.

1.1 Collisions in cars due to pedal misapplication

Several car manufacturers have experienced a high number of SUA complaints, some of which have led to formal investigations. For instance, in 2021, an investor petitioned for NHTSA to investigate more than 200 SUA collisions involving Tesla vehicles[2]. The Tesla owners claimed that the vehicles were suddenly and unexplainably accelerating, causing the vehicles to hit trees, fire hydrants, walls, and other cars. This investigation concluded that these incidents were likely a result of user error (possible pedal confusion). Tesla released a statement shortly after claiming that their autopilot system currently prevents up to 40 crashes per day due to pedal confusion[3].

[1]https://www.london.gov.uk/who-we-are/what-london-assembly-does/questions-mayor/find-an-answer/pedal-confusion-unintended-acceleration-incidents-june-2016-present-2#:~:text=For%20the%20period%20April%202010,a%20result%20of%20a%20collision

[2]https://www.washingtonpost.com/transportation/2021/01/08/tesla-brakes/

[3]https://electrek.co/2022/08/22/tesla-autopilot-prevent-40-crashes-per-day-wrong-pedal-errors/

In 2008, Toyota recalled millions of vehicles due to what were described as "sticky pedal" incidents[4] in which users reported their vehicles accelerating without their intent. This launched a ten-month study by the U.S. Department of Transportation (DoT) into the potential causes of SUA in Toyota vehicles. After evaluating the Toyota vehicles, the DoT concluded that "NASA found no evidence that a malfunction in electronics caused large unintended accelerations"[5]. The two safety mechanism defects identified that were responsible for some of these incidents included accelerator pedals "sticking" and a design flaw which led to pedals being trapped under floor mats. However, after the review of black box devices, driver error or pedal misapplication was found to be responsible for most of these cases of unwanted speeding[6]. Based on these findings, NHTSA began researching whether better placement and design of pedals can reduce pedal misapplication. Toyota later released its new Acceleration Suppression System, which detects obstacles and prevents the vehicle from accelerating if the acceleration pedal is pressed[7]. The Acceleration Suppression System is further discussed in Section 3.4.

1.2 Collisions in buses due to pedal misapplication

The problem of pedal misapplication amongst bus drivers has recently been highlighted by Unite, the union representing over 20,000 London bus workers[8]. This growing concern has been amplified by the introduction of newer buses, particularly those fitted with electric powertrain. This is because electric buses accelerate faster than diesel buses, reducing the response time available to depress the brake pedal if pedal misapplication occurs. Collisions resulting from pedal misapplication involving buses have been highlighted on news sites. One example included a fatal bus crash at Victoria station in 2021 in which a bus driver accelerated into a pedestrian[9]. TfL investigated this incident and suspected it was due to pedal confusion[10]. Unfortunately, the pedestrian was pronounced dead at the scene. Unite

[4] https://www.manufacturing.net/automotive/blog/13110434/the-2009-toyota-accelerator-scandal-that-wasnt-what-it-seemed

[5] https://www.transportation.gov/briefing-room/us-department-transportation-releases-results-nhtsa-nasa-study-unintended-acceleration

[6] https://www.lambopower.com/forum/index.php?/topic/49891-dot-report-driver-error-to-blame-not-defect-in-toyota-sudden-acceleration/

[7] https://global.toyota/en/newsroom/corporate/33012068.html

[8] https://www.unitetheunion.org/news-events/news/2021/december/unite-says-tfl-must-act-on-bus-pedal-confusion-to-keep-londons-roads-safe/

[9] https://www.standard.co.uk/news/london/deadly-bus-crash-victoria-london-melissa-burr-driver-may-have-confused-brake-b970223.html

[10] https://www.london.gov.uk/who-we-are/what-london-assembly-does/questions-mayor/find-an-answer/pedal-confusion-danger-electric-buses#:~:text=TfL%27s%202%20December%202021%20discussion,reported%20by%20the%20Evening%20Standard%20 (

has continued to put pressure on TfL to act and resolve this problem. Many have raised concerns that the pedal design of electric vehicles as well as driver fatigue, are what contribute to the increased likelihood of pedal confusion[11]. After the development of TfL's Bus Safety Standard (BSS), a pedal indicator light was introduced as a requirement for new buses since 2019 and brake toggling since 2021[12]. These mitigation techniques will be further discussed in Section 3.4.

1.3 Project objective

As seen from the various real-world cases presented, pedal misapplication is considered an important cause of serious and fatal collisions. This report presents the evidence review conducted to explore the topics of pedal misapplication.

The aim of the study is to examine the driver and vehicle characteristics associated with pedal application errors, crash contributing factors, and proposed mitigation systems by conducting a rapid review of literature and analysing UK in-depth accident data (RAIDS).

The findings of this study can help the Department for Transport to determine the magnitude of the problem of collisions associated with pedal misapplication and help define an agenda for further improvements in safety standards.

1.4 Report structure

This report is structured as followed:

- Section 2 details the methods used to conduct the rapid literature review. The methods used to interrogate the in-depth RAIDS database are also presented, along with how injuries are classified within the database.
- Section 3 presents the result of the rapid literature review, including outcomes, causes and mitigations of pedal misapplication, as well as the limitations of the review.
- Section 4 provides the collision landscape of all the pedal misapplication cases identified within the in-depth RAIDS database through analysis of the data.
- Section 5 presents three case studies taken from the pedal misapplication cases identified within the in-depth RAIDS database. The 3 cases are described in detail to aid understanding of identified topics.
- Section 6 presents a discussion of the findings from Sections 3, 4 and 5 to gain further insight into the causes, outcomes and mitigations of pedal misapplication collisions.

---

[11] https://london-post.co.uk/unite-says-tfl-must-act-on-bus-pedal-confusion-to-keep-londons-roads-safe/

[12] https://www.london.gov.uk/who-we-are/what-london-assembly-does/questions-mayor/find-an-answer/pedal-confusion

2 Methods

This study employed two key methods: a systematic rapid analysis of literature and analysis of real-world crash data in order to understand the characteristics of pedal misapplication related collision, its contributory factors and identify potential mitigation system to avoid such collision. This section details the methods used.

2.1 Rapid literature review

To explore the topic of pedal misapplication, a systematic rapid literature review was performed. A list of key search terms was created and was separated into three levels (see Table 1 overleaf). The first level being the overarching topic at hand. The second level terms were used to refine the search output to better target the specific areas of interest (causes, outcomes, and mitigation measures), while third level terms were used to further refine output as needed. Multiple searches were then conducted using the Individual search terms as well as varying level combinations to generate relevant results.

Given the topic at hand, TRID (Transport Research International Documentation) was deemed the most likely source of relevant literature as it is an integrated database that provides access to 1.4 million records of transportation research worldwide. Google scholar was also used as it would be able to capture evidence from other sources beyond TRID. Search output was given a rapid assessment on its quality and relevance to the topic of pedal misapplication and aims of this review. Items of literature deemed suitable at this stage were included a spreadsheet for review. These items were then reviewed in full with summary notes on each study's purpose, method, and findings being recorded.

Overall, 18 pieces of academic literature and 10 related media articles were included in the final review. The findings from the review of collected literature are detailed in Section 3.

Table 1: Search terms used for the literature search.

1st level		2nd level		3rd level
Pedal misapplication	AND	Accident*	AND	Risk*
Pedal confusion		Crash*		Outcome*
Sudden unintended acceleration (UA)		Mitigat*		Benefit*
Unintended braking		Road*		Consequen*
Pedal error		Environment*		Standard*
Pedal application error		Safe*		Evaluat*
Brakes failure		Prevent*		Solution*
Pedal misplacement		Driv*		Awareness
Harsh braking		Mistak*		Implication*
Unexpected acceleration		Avoid*		Human Factors
Harsh accelerating		Injur*		Behaviour*
		Educat*		Feedback
		Incident*		Review*
		Bus*		
		Error*		
		Fatal*		
		Distract*		
		Correct*		
		Colli*		
		Report*		
		Electric*		
		Vehicle*		
		Slip*		
		Miss*		
		Sudden*		
		Control*		
		Event*		
		Instance*		
		Hit*		
		Cause*		

2.2 Crash data analysis

Crash data collected between 2012 and 2023 for the UK Road Accident In-Depth Study (RAIDS) was used in this study. RAIDS is managed by TRL on behalf of the UK Department for Transport. The study is designed to create an evidence base to support improved road safety. The development of appropriate and cost-effective policies, technologies, and solutions to prevent future loss of life and injury in road traffic collisions depends on reliable data at the required level of detail to provide a deep understanding of road collisions (vehicle, user and environment) and the mechanisms which result in road collisions and injuries.

RAIDS investigations differ from those of the police because they are designed to understand all factors influencing a collision and its outcome rather than necessarily determine responsibility. Typically, the RAIDS team will investigate around 200 cases per year; these are a mix of investigations carried out at the live collision scene and retrospective investigations based on vehicle examinations and analysis of police collision reports. This information is held in a single comprehensive database which provides an invaluable evidence-based research tool which is used extensively in road safety improvement programmes, medical research, vehicle standards and design. Since the start of RAIDS, over 150 research studies have accessed RAIDS for research projects.

The injury information is recorded within the RAIDS database using the Abbreviated Injury Scale (AAAM 2008). The Abbreviated Injury Scale (AIS) is an anatomically based injury coding technique developed by Association for the Advancement of Automotive Medicine (AAAM) to classify and describe the severity of injuries (AAAM 1990). The AIS is a seven-digit numeric code which contains information about both the severity of the individual injury and the injury location on the body. The AIS score indicates the relative risk of ‘threat to life’. The threat to life scale is on a 6-point ordinal scale ranging from minor (AIS 1) to currently untreatable (AIS 6) and are as follows:

- 1 = minor injuries
- 2 = moderate injuries
- 3 = serious injuries
- 4 = severe injuries
- 5 = critical injuries
- 6 = untreatable injuries (usually non-survivable)

The AIS is also the basis for the Maximum AIS (MAIS) measure. The MAIS is the highest single AIS injury that a person with multiple injuries has sustained. The MAIS for the occupant is always either equal to or greater than the AIS value for the injury in the individual region.

For this study, RAIDS database was interrogated to identify cases where the driver of a vehicle had been recorded with the interaction code of: ‘loss of control due to incorrect operation of the controls or the driver had the causation factor of ‘Control confusion: pedals/auto gearbox etc’ coded as ‘Known’ or ‘Suspected’. Finally, a text search of the accounts of summary was conducted on the terms ‘pedal confusion’, ‘control confusion’ and ‘pedal misapplication’.

All the cases matching one or more of the searches was reviewed. Cases which didn’t match the selection criteria such as collisions involving incorrect steering input, the drivers shoe becoming stuck between the pedals or were the pedal was ‘missed’, were discounted.

3 Results: Rapid Literature Review

This section details the findings from the review of evidence, separated into outcomes (crash characteristics), causes (driver characteristics, driving style, and vehicle characteristics), and mitigation measures.

3.1 Crash characteristics

According to NHSTA, a SUA episode that takes place purely during start-up events and can be described as "unintended, unexpected, high-power accelerations from a stationary position or a very low initial speed accompanied by an apparent loss of braking effectiveness." (Pollard, 1989). NHTSA also concluded that pedal misapplication was the most probable explanation for SUA when no vehicle malfunction was evident. Contrary to the NHTSA definition of SUA episodes, studies such as that conducted by Schmidt and Young (2010) have found that over 92% of pedal misapplications occur **during the driving cycle rather than during start-up**. Schmidt and Young reviewed the police collision-report database from North Carolina which contains over one million collisions of all types, including verbatim and written statements from those involved in the collision. The database was searched for key words that characterise a pedal misapplication event such as 'sudden', 'accelerator stuck', and 'unexpected'. They found that 3,740 collisions were caused by pedal misapplication These collisions were classified into those which occurred during parking (further classified into forward and backward direction) or driving (turning, slowing, stopped, or other), and if the driver was hurried, unhurried, or distracted. They found that only 279 of the 3,740 incidents were considered parking operations, 268 were considered hurried, and 255 were distraction. Further characteristics of the collisions resulting from pedal misapplication can be seen below in Table 2.

Table 2: Pedal-error type as a function of driving circumstances (Schmidt and Young, 2010)

Action	Type of pedal error	
	Slip	"Wrong pedal"
Stopped	604	69
Slowing	613	180
Turning	97	134

This would suggest that the NHTSA definition of pedal misapplication episodes resulting in SUA does not fully encapsulate the problem and that contrary to belief, pedal misapplication often occurs **after initial start-up, in unhurried conditions, whilst the driver is turning** (as more data was recorded for "wrong pedal" episodes compared to slips when reviewing turning).

In addition to this, Smith et al. (2021) further examined the characteristics of crashes resulting from pedal misapplication. This study also reviewed crash descriptions and narratives in the North Carolina state crash database (between 1st January 2014 and 31st May 2020) alongside the National Motor Vehicle Crash Causation Survey (NMVCCS) database (between 1st January 2005 and 31st December 2007). Similar to Schmidt and

Young's (2010) approach, Smith et al. used key search terms to identify 33 Crashes resulting from pedal misapplication in NMVCCS (representing 1,944 annual crashes in the US or 0.22% of the sample) alongside 3,274 confirmed crashes resulting from pedal misapplication from the North Carolina dataset (representing 0.18% of crashes in the database and 504 crashes per year). According to both datasets, over 50% of pedal misapplication collisions resulted in **rear-end or roadside departure crashes**. Crashes resulting from pedal misapplication in North Carolina also had higher proportions of **commercial and residential crash settings** (over 90% combined) compared to other settings (e.g. rural environments). Crashes resulting from pedal misapplication tended to occur on **roads with lower speed limits** compared to other crashes. Emergency stopping, parking manoeuvres, and reaching out of the vehicle to interact with objects (e.g. card readers) were also commonly linked with pedal application incidents (Xi, 2015).

Both Schmidt and Young's (2010) and Smith et al.'s (2021) studies were limited by the inclusion criteria of respective databases. It cannot be taken as certain that both these studies were able to access all examples of collisions resulting from pedal misapplication in their analyses. This is because collisions that result in property damages that cost less than $1,000 are not included in the North Carolina database. Similarly, collisions that occur in parking lots without the need for emergency medical services are not included in the NMVCCS database. These studies also utilise written narratives to identify collisions resulting from pedal misapplication, and such retrospective, self-reported data may not be reliable because drivers may not accurately recall the situation or admit to being at fault. After reviewing these limitations, we would expect the current figures to more likely be an underestimate of the amount of pedal misapplication incidents that occur in reality.

3.2 Driver characteristics

3.2.1 Gender and Stature

Alongside examining crash characteristics, Smith et al. (2021) also explored the effect of driver characteristics such as gender on pedal misapplication. The study identified that of the drivers that cause collisions resulting from pedal misapplication, the **majority are female**. This is interesting because the majority of drivers involved in all crashes in both datasets were male. According to the NMVCCS, 64% of drivers involved in pedal misapplication incidents were female, though females only accounted for 53% of the driving population in North Carolina. In a chi-square test for both gender and sex, Smith et al. found that there was a significant increase in the female sex and gender representation in collisions resulting from pedal misapplication compared to all collisions. They also identified that drivers involved in collisions resulting from pedal misapplication were shorter in stature compared to all collisions. As being shorter is often associated with being female and vice versa, it is difficult to identify which of these factors (if any) is more of a risk factor for pedal misapplication.

Analysis conducted by the US Department of Transportation (2012) also found that females were overrepresented in collisions resulting from pedal misapplication. This analysis concluded that females account for 63% of all 2,400 collisions resulting from pedal misapplication, but only account of 44% of all total crashes (for the period 2004-2008).

One suggested reason for why females are overrepresented in these datasets is that on average they are **shorter in stature and have smaller foot sizes**. In a dissertation conducted by Xi (2015), the relationship between driver stature, shoe length, and foot pivoting was explored. Twenty-six participants over the age of 60 were recruited through physician referrals to the Driving Rehabilitations Program at the Roger C. Peace Rehabilitation Hospital (RCP). Participants were asked to complete driving tasks on a pre-defined route including a stopping task. The stopping task involved participants performing 10 stops at stop signs located in a residential area. The study found a significant positive correlation ($r > 0.5$) between the percentage of **foot pivoting** and the driver's stature. Thus, suggesting that taller drivers are more likely to use foot pivoting rather than foot lifting when pressing different pedals. There was also a strong positive correlation between percentage of pivoting and shoe length ($r > 0.5$). Xi suggests that compared to foot lifting, foot pivoting only requires the driver to rotate their foot. This could ensure that the driver has better contact with the pedal and could allow them to use the floor as a reference point in order to help distinguish between the pedals. It should be noted that no pedal misapplication episodes were observed in this study and therefore this hypothesis is merely speculative. More research is needed to clarify the relationship between stature, foot size, and pedal misapplication. However, this could help to explain the factor of gender.

3.2.2 Age

In addition to females being overrepresented in reported crashes resulting from pedal misapplication, **older drivers** are also overrepresented. This appears to be one of the more widely discussed driver characteristics associated with collisions resulting from pedal misapplication.

For example, in the Daegu/Gyeongbuk region of the Republic of Korea one study used objective evidence (such as collision videos) to show how pedal misapplication is caused by pedal confusion (Lee & Lee, 2022). In this study the researchers reviewed 27 collisions that were claimed by drivers to be a result of pedal misapplication. They found that pedal confusion occurs in two stages, the first being initial sudden confusion (when the accelerator is pressed rather than the brake pedal) and the second stage is failure to correct (the driver fails to correct their foot positioning to press the brake pedal). They found that of the 27 collisions resulting from pedal misapplication, 21 were thought to be due to pedal confusion. They also found that of the 21 drivers who experienced pedal confusion, the average age was 63.5 (±10 years). This could mean that older adults are more likely to experience both stages of pedal confusion thus leading to a collision resulting from pedal misapplication. It should be noted that this study has a very small sample size and thus the findings of average age are not generalisable. However, the hypothesis that older drivers are more likely to cause collisions resulting from pedal misapplication has academic support. Smith et al. (2021) also identified an overrepresentation of 65-94-year-olds when they examined NMVCCS and North Carolina state crash databases for crashes resulting from pedal misapplication. They found that the highest proportion of collisions resulting from pedal misapplication for any single age group involved drivers aged 65-74 years. This age group accounted for over 30% of all collisions resulting from pedal misapplication but only 8% of all collisions.

On the other hand, Smith et al. (2021) also found that **younger drivers** accounted for a significantly larger proportion of collisions resulting from pedal misapplications in the NMVCCS database only. In this database, drivers aged under 25 made up 34.5% of collisions resulting from pedal misapplication and 27.4% of all total collisions. There would appear to be some support for Smith et al.'s hypothesis as has already been discussed by Xi (2015) in the previous section. It could also be related to driver experience as younger drivers tend to be less experienced and may not even hold a full licence. More research is needed around this area in order to confirm why younger drivers are overrepresented in these databases.

The reasons why older drivers are overrepresented in crashes resulting from pedal misapplications could be due to the accuracy of their feet when hitting the pedals, thus leading to the first stage of a pedal misapplication episode: pressing the wrong pedal (Lee and Lee, 2022). Wu et al. (2015) examined the variations in **drivers' foot behaviour**, its relationship with pedal misapplication, and how it can vary between age groups. This was a driving simulation study which used 43 healthy drivers as participants. The driving scenarios involved driving through traffic signals in various locations which appeared for varying lengths of time (e.g. signal length ranged from 0.76 – 1.13 s and time interval between signals ranged from 0.33 – 2.30 s)) with surrounding traffic. Pedal applications were classified based on the trajectory of foot movements according to a video analysis. Pedal response time was also measured from the time the traffic signal appeared to the moment the participant touched either pedal. The study found that most applications were direct hits with each person having multiple direct hits (n=73 for those 75 and older, and n=83 for those 21 and younger). At a red signal, all participants were 28 times more likely to hesitate and three times more likely to respond with the wrong pedal, slip, or miss. Middle-aged (26-55 years old), older (60-74 years old), and the oldest drivers (>74 years old) were more likely to not directly hit the pedal compared to the youngest group, with the largest number of corrected trajectories being between those 60-74 years old.

It should be noted that the use of a simulator is a somewhat unfamiliar and artificial environment for participants. Therefore, the participants' natural driving behaviour may be different to what they displayed in the simulation. However, the use of the simulator does guarantee that the participants' environment is controlled because the researcher can programme the scenarios to be identical for each participant, making results more comparable than in a real-world setting.

3.2.3 Cognition

Because age is linked with cognitive decline, it is necessary to consider the relationship that cognition has with foot behaviour and pedal misapplication. Kawai and Nakata (2022) hypothesised that older adults would show greater brain activity and slower reaction times compared to younger adults when following an instruction signal to press a button with their hands or feet. This study involved 44 participants (20-74 years old) completing a simple reaction time task. The task required individuals to press one of two buttons with either their hand or foot in response to a stimulus. A NIRS unit was used to measure temporal changes. The results of the study showed that **reaction times** were longer in older adults and there was **greater brain activation** across the pre-frontal cortex (PFC) compared to younger adults. According to the authors, this activation could suggest that older adults require additional brain circuits to compensate for any declining executive functions. However, the authors also noted that there was **no difference in accuracy** between the age groups. According to Lee and Lee (2022) this could mean that older adults are more likely to make errors at the second stage of a pedal misapplication episode (i.e. failing to correct). Similar to a simulator study, this study is an artificial task. Seeing stimuli and pressing buttons in response is not comparable to driving. However, it does allow researchers to monitor cognitive functioning in a controlled environment.

Indeed, cognitive functioning is an important factor when considering pedal confusion, and age is a primary risk factor for cognitive impairment. It is estimated that 10% of healthy individuals over the age of 65 experience **cognitive impairment** (Sager, 2003). This could partially explain why older drivers are overrepresented in collisions resulting from pedal misapplication in databases. One study conducted by Freund et al. (2008) assessed to what extent specific cognitive functions contribute to pedal errors among older drivers. For this study, 180 participants aged 65 and over completed three cognitive tests. This included: the Mini Mental State Exam (MMSE), which assesses orientation, attention, recall, language, and constructional ability; the Clock Drawing Test, which relies on visuospatial, constructional, and higher-order cognitive abilities; and Trail Making Part A and B, which are tests for attention, sequencing, mental flexibility, and motor function. Participants also completed a 30-minute driving evaluation in a simulator where they were instructed to drive normally through an urban course programmed to require the execution of everyday manoeuvres. Pedal misapplication events were defined as the inappropriate acceleration or failure to decelerate or transition from accelerating to braking when required. The study found age to be a significant predictor of pedal misapplication events among the oldest participants (84-89 years old). They identified the Clock Drawing Test as the best predictor of pedal misapplication suggesting that **executive function is a key component involved in safe driving**. Therefore, the presence of executive dysfunction in older adults could lead to more driving errors, such as pedal confusion and misapplication. This is because during a pedal misapplication episode the driver could “freeze up” due to stress, resulting in an inability to react safely and appropriately, and being less able to correct the pedal misapplication.

It should be noted that the authors of this study highlighted that 70% of the drivers who experienced a pedal misapplication event verbalised their inability to slow or stop the vehicle when their foot was on the acceleration pedal. This would suggest that they recognised the need to decelerate highlighting true pedal confusion. The authors claimed that the same could not be said regarding the 30% of drivers who did not verbalise this. They hypothesised that this could be a foot misplacement error rather than pedal confusion. More research needs to be done regarding other reasons behind pedal misapplication to define the true impact of pedal confusion.

Further research examined whether pedal misapplication errors occur more frequently when a task is interrupted by a non-driving task for a longer period because the driver requires **memory activation** in order to resume pursuing their previous goal (i.e. pedal manipulation; Hasegawa et al., 2021). For this study, 40 younger adults (evenly split by gender, mean age = 21.73) and 40 older adults (evenly split by gender, with no signs of dementia, mean age = 71.35) completed a pedal response task which involved stepping on either a brake or accelerator pedal. Between these tasks the participants were also required to complete an interruption task or varying lengths which consisted of touching numbers in ascending order as quickly as possible. Participants would then be instructed to brake or accelerate at the end of the interruption and not looking at the display monitor. Interruption tasks varied in length from 30-120 seconds. During the interruption task the monitor in front of the participant would change to display either a green light or red light. The participant, when hearing a tone to recognise the end of the interruption task, would then look back at the display monitor and either accelerate or brake according to what colour light was displayed. Participants were told to do this as quickly and as accurately as possible. This study found that pedal misapplication rate was higher in long interruption conditions compared to short interruption conditions in older adults (3.8% vs. 0.5%). This was not the case for younger adults in which no statistically significant difference was found. Although accuracy decreased for older adults in the long interruption conditions, speed maintained the same. However, speed was worse for older adults compared to younger adults in all conditions. The authors concluded that according to this study pedal, misapplication is influenced by a decrease in activation for goals and that this is caused by long interruption periods and specific to older adults. The study had similar findings to Kawai and Nakata (2022) such as that reaction times were longer in older adults. A study by Gaspar and McGehee (2019) identified that the critical point to brake in response to pedal misapplication is 1s. Therefore, older adults may not have the cognitive ability to achieve this reaction time thus contributing to their overrepresentation in collisions resulting from pedal misapplication databases.

3.2.4 Driving style

Driving style is also thought to contribute to the cause of pedal misapplication, specifically how drivers use their brakes and position their heels, feet, and backs. As discussed in Section 3.2.1, Xi (2015) suggested that **foot pivoting** is important for accuracy when using pedals. Other studies have also examined how the **positioning of the feet and body** may increase the likelihood of pedal misapplication. For example, Wu et al. (2017) wanted to examine the different types of pedal application and how this is related to foot, heel, and back positioning prior to and during pedal applications. To examine this, 30 participants took part in a naturalistic driving task which involved them driving their own car; however, it is unclear for how long and what route participants were asked to drive. An event-triggered video recorder was used to capture the pedals and the heel of the driver. Recordings would start during the start-up sequence, parking sequences, the last minute of drive before the ignition is turned off, and during hard accelerating or hard braking. They observed 57 pedal errors which included wrong pedal pressing (n=13), missing the pedal (n=33), both pedals pressed (n=7), and pedal slip (n=4). They also observed 565 notable pedal responses which included incorrect trajectory (n=284), uncertainty (n=168), and back pedal hook (n=113). The researchers found that the driver's right foot placement at the time of the pedal event and immediately before were important when predicting the pedal application type. The study found that if the **driver's foot was on the accelerator pedal** prior to the event, the driver was 10 times more likely to have an incorrect foot placement on the brake pedal. If the driver's foot was on the brake pedal prior to the event they were less likely to make a foot placement error. They also found that if the driver's heel was placed on the floor and their back positioned away from their seat (leaning forwards) during an event, the driver's feet would be less likely to be in transition mode (moving from one pedal to another). The researchers noted high classification error for this research as it had a small sample size and huge variation in drivers' foot placement. However, considering specific foot movements and seating positions may provide insights on appropriate pedal applications to avoid pedal misapplication.

In a separate study, Gaspar and McGehee (2019) examined how drivers reacted to pedal misapplication (specifically SUA) and what type of braking behaviour could lead to a potential collision. Younger (n=16, ages 21-45) and older (n=16, ages 60-80) drivers completed a 15-minute drive through rural and urban environments in a controlled high-fidelity driving simulator. During a parking task, drivers experienced a scripted SUA event in which the car would accelerate for 4s as if the accelerator pedal was completely depressed. Full depression of the brake could "override" the SUA bringing the car under control. After reviewing the videos, it could be observed that all drivers responded by initially depressing the brake pedal. A hierarchical cluster analysis on the time series brake response data was then performed. Three braking behaviours were identified: **hard braking** (braking with greater than 125 lbs (556 N) of force within 1.5 s), **brake pumping/gradual braking** (braking to a maximum of approximately 125 lbs of force within 5 s) and **light brake press** (brake force less than 75 lbs over the span of 5 s). Seven drivers crashed during the SUA event and all these drivers made light braking responses. No crashes were observed for hard or gradual braking responses. It was noted that drivers with light brake responses travelled considerably farther into the car park, making them more likely to make contact with other vehicles and obstacles. The results also suggested that drivers take roughly 1 s to perceive a pedal misapplication episode and the critical window to respond to pedal misapplication appears to be between 0.5 and 1.5 s. The researchers pointed to a need for advanced driver assistance systems (ADAS) which could be used to make the initial decision of what to do for the driver (i.e., brake) and prevent hesitation leading to a potential collision resulting from pedal misapplication.

On the other hand, the methodology for this study (Gaspar and McGehee, 2019) has limitations. A simulated SUA event to represent pedal misapplication may not reflect a real-world pedal misapplication event. This is because the driver may not even have her/his foot on the pedal and may instantly assume it is a simulator/computer error. Therefore, the driver's feet may not have been in the correct position to respond to this event impacting braking pattern and response times. This limitation should be considered when discussing this studies results.

3.3 Vehicle characteristics

Many drivers who have been involved in collisions resulting from pedal misapplication have pointed towards the vehicle properties for being at fault. This includes software, pedal positioning, and pedal location to name a few.

In a report for TfL, Rogers (2022) created and distributed a survey to 593 bus drivers and operators and conducted workshops with 86 stakeholders to review possible causes of pedal confusion. One possible cause that was highlighted was **pedal configuration** (the spacing between the pedals). During the workshop, attendees discussed how the pedals tend to differ between different bus models. In particular, electric buses and the New

Routemaster bus had pedals that were particularly close together making hitting the pedals separately difficult to achieve. It should be noted that this data is both **self-reported and retrospective**, much like other pedal misapplication data sources. As drivers often do not want to appear at fault if they are the cause of a collision resulting from pedal misapplication, there is potential for some bias in this data and the reported problem of pedal configuration is overstated.

An earlier study by Collins et al. (2014) utilised the North Carolina State Crash Database (including narratives of 1,430 pedal misapplication incidents between 2004-2008) to analyse the pedals, vehicle controls, and seats of cars from a high-reported pedal misapplication populations and a low-reported pedal misapplication populations (rates of pedal misapplication per 100,000 vehicles) to see which variables correlated with pedal misapplication. It was found that the **stepover** (i.e. the distance between the surface plane of the brake pedal and the surface plane of the accelerator pedal) **and accelerator position** were most correlated with misapplication rate, but no single variable had a high correlation to the misapplication rate. Stepover appeared to have an inverse correlation to pedal misapplication rate (the smaller the stepover the higher the misapplication rate). It was also found that both the **position of the vehicle controls and their estimated position relative to the seat** showed some correlation with pedal misapplication. When these were taken in conjunction with average driver characteristics (age, gender, height), this interaction was more strongly correlated with pedal misapplication. The researcher then noted that optimal pedal dimensions for one demographic may not be optimal for another. Perhaps further research could highlight the optimal pedal configuration according to driver height. Drivers can alter their seat height and positioning to better position themselves to use the pedals, but they do not have the ability to alter the pedals themselves. It could be argued that if drivers were able to alter their pedal positioning this could result in more pedal misapplication events taking place as drivers may struggle to adjust, especially if the driver frequently changed this configuration. Therefore, further research is needed to help identify how vehicle manufacturers can assist in creating optimal pedal configuration for drivers and reduce the likelihood of potential pedal misapplication.

This review found little evidence to prove that transmission type (automatic or manual) may have an impact on likelihood of pedal misapplication. The data used in most of these studies is based on automatic transmission passenger cars in the US so it is not possible to assess the difference in pedal misapplication errors among both automatic and manual transmission vehicles. There have been a number of brief references in academic text that pedal misapplication occurs less often in manual transmission cars (Smith, 2022). For example, Ichiro and Kazunori (2015) discussed in their report that although from 2000-2012 there were approximately 6,900 pedal misapplication cases in Japan, there were no reports submitted by manual transmission vehicles. Unfortunately, the authors do not note the proportion of manual transmission vehicles in Japan at the time. We were unable to find any evidence to support this or reasons as to why this may be the case. Xi (2015) commented on the better alignment of manual transmission vehicles as those that drive a manual vehicle frequently use the clutch pedal meaning that they adjust their seating position to be symmetric to the centre of the seat. It was suggested that perhaps this helps the driver to distinguish between the two pedals. It is important to understand if and how the design of vehicles fitted with an automatic transmission contributes to the likelihood of pedal misapplication because the popularity of automatic transmission vehicles in the UK is significantly increasing. In 2015, just over 45,000 (out of 723,000 total passes) of national driving test passes were in automatic vehicles compared to 2020 which increased to 80,000 (out of 734,000 total passes)[13]. It is also important to consider the increase in electric vehicles on the road and if this will also have an impact on the number of crashes caused as a result of pedal misapplication as the majority of electric vehicles are automatic. Approximately 120,000 electric cars were sold worldwide in 2012 and according to trends in electric light duty vehicles the same number was sold within just a week of 2021[14]. Future research should examine the properties of automatic, manual, and electric vehicles in order to distinguish what features may have an impact on pedal misapplication.

3.4 Mitigation techniques

To minimise the potential damage and injuries pedal misapplication can cause, many researchers have proposed mitigation systems.

One study by Ichiro and Kazunori (2015) sought to provide a solution from the viewpoint of human factors to the numerous collisions that they observed had been caused by pedal misapplication in automatic vehicles. The researchers highlighted the pedal layout (the similarity of the accelerator and brake pedal placement and identical method of operation) of most automatic vehicles to be the contributing factor in why 6,900 collisions resulting from pedal misapplication happen annually in Japan. They discussed six mitigation systems:

- **Hand-controlled throttle** (HAC-T). This system replaces the foot-controlled pedal with a lever positioned on the vehicle’s centre console operated the driver's thumb. Other elements of a HAC-T system include a brake pedal (positioned where the driver wants it i.e. left, or right). The authors describe this system as the most promising system for preventing pedal misapplication. However, research is needed to understand the knock-on effect of having a hand-operated throttle as the hands are already responsible for many driving tasks such as indicating, steering, lights, wipers and centre console systems and there may be a risk of adding another responsibility on the hands during driving.
- **Automatic braking system (ABS)**. ABS may use radar, sonar, infrared, or camera-based instrumentation as obstacle detection systems. The system includes the function of preventing pedal misapplication collisions while parked and starting the driving cycle. It can also provide emergency braking at high speeds as well as an alert function for lane departure. One limitation of this system is that it cannot override controlled acceleration, so cannot completely mitigate against pedal misapplication. The authors described this system as “slightly incomplete” for preventing collisions resulting from pedal misapplication. This would support Tesla’s claim that their

[13] https://www.wearemarmalade.co.uk/driver-hub/news/is-learning-in-an-automatic-the-new-normal#:~:text=In%20Britain%2C%2090%25%20of%20driving,on%20the%20road%20that%20year.

[14] https://www.iea.org/reports/global-ev-outlook-2022/trends-in-electric-light-duty-vehicles

autopilot sensors and emergency automatic braking system prevents up to 40 pedal misapplication collisions per day. However, the system is not likely to fully eradicate user error.

- **Safe driving assist system** (SDAS). The SDAS automatically turns off the engine when the driver fully depresses the accelerator pedal. There is no further detail provided regarding whether the engine will always cut off when the accelerator is fully depressed or if there is a certain amount of time that the pedal needs to be spent fully depressed before the engine will cut off. One limitation for this system is that when the engine is turned off suddenly, collisions may occur.
- **Stop pedal**. This system includes the installation of an accelerator pedal connected to the brake pedal suspension rod. This means that when the accelerator is fully depressed (or reaches a pre-determined position) the accelerator function is automatically released slowing the vehicle down. When the driver releases the accelerator pedal the pedal will return to normal functioning. Theoretically, a driver could control the vehicle using only the accelerator pedal as the accelerator pedal now also functions as method to slow the vehicle down. One limitation for this system is that unintentional braking rather than necessary accelerating may occur. This could also cause a collision.
- **NARUSE pedal**. This device is installed onto the existing brake pedal. The accelerator pedal becomes a long, narrow metal device that sits slightly raised to the right of the pedal. The accelerator pedal operates by rotating the foot clockwise using the right instep. The position of the accelerator pedal allows the driver to rest her/his foot on the brake pedal whilst using the accelerator simultaneously. This rotation function enables the driver to distinguish which pedal is being used. Given how this system appears to complicate the driving task, likely increasing the cognitive load required to operate a vehicle to an unreasonable degree, it is unlikely that this is a viable system for mitigating pedal misapplication. Future research efforts would likely be better placed focusing on alternative solutions, such as the HAC-T.
- **Brake system for left leg operations** (BLO). The brake pedal is installed on the far left of the driving floor meaning the driver will use separate legs for each pedal. Three bolts are installed on the brake pedal to allow the driver to place her/his foot on the pedal easily throughout the journey. This is similar to how formula one drivers use their pedals. Although the authors do not note the type of car this system may be appropriate for, we could assume this is for automatic vehicles as the design doesn't seem to include a clutch nor mention where this would be situated.

Further research by Pistak, Edwards and Huysamen (2022) discussed the problem of pedal confusion in bus drivers and the design and recommendation of a pedal indicator icon was made to help prevent pedal misapplication in bus drivers. The authors reviewed national and international standards regarding the design and restrictions that apply to bus warning icons. Bus manufacturers were consulted regarding the feasibility of potential designs and their opinions from the perspective of bus drivers. The final designs were then incorporated into an online survey which was distributed amongst 188 London bus operators to disseminate to their drivers. The survey required the participants to make judgements about what each symbol may mean and why. After their interpretation was recorded, the real explanation of the symbol was provided. Solutions were then ranked in order of favourite to least favourite. The design that was most preferred was a yellow and black icon showing a foot on a pressed pedal.

It should be noted that even though this design was the most correctly interpreted design choice, nearly half of participants still interpreted the meaning of the symbol incorrectly. Thus, the researchers suggested training bus drivers to understand the new icon. The researchers hoped that implementing this design would allow bus drivers to understand when their foot is on the accelerator pedal rather than the brake allowing them to recognise and correct their mistake before a collision resulting from pedal misapplication occurs.

Earlier research identifying possible solutions for pedal confusion in bus drivers was conducted by Bright and Lock (2011). The contributing factors that the authors considered cause pedal confusion were categorised as poor proprioception (sense of position of limbs), high workload while driving, inability to recover from error, and severity of consequences. Possible solutions were then developed using a psychological model of pedal misapplication incidents. These solutions included:

- **Pedal design modifications.** This included standardisation of pedal layout, changing the size of pedals, increasing the distance between pedals, providing differentiation in accelerator and brake options, and integrated tactile indication of accelerator operations. However, it should be noted that optimal pedal design may differ from driver to driver according to characteristics such as driver heigh and foot size. A basic proof of concept should be done to examine whether modifying pedal layout indeed reduces pedal misapplication.
- **Engine cut-out when driver door is opened**. This would require significant organisational input (to endorse the time to arrange the workstation) and trials would need to be run to ensure the technology had no unintended consequences.
- **Improvement of seat adjustment controls**. Standardising seat adjustment controls for buses would require prototyping and trialling of preferred solutions. Consideration would need to be given to the design and implementation of such a change to account for the needs of different organisations.
- **Training** (pedal misapplication specific). A highly experienced driver/trainer should be rolled out to drivers to provide training material on reducing pedal misapplication.

In a study conducted by Runham et al. (2018), **brake toggling** was recommended as a solution for pedal misapplication amongst bus drivers. Brake toggling refers to an additional press of the brake pedal before starting the vehicle from a stationary position to update the driver's recent memory of the brake pedal position. Runham et al. (2018) suggested this should be introduced to buses when the driver needs to move off from a bus stop. This study involved full-scale trialling and testing in a realistic environment to determine whether the improvement was viable. The solution allows the driver to re-initialise their right foot/driving position to improve foot proprioception and muscle-memory of pedal positions. It is associated with low levels of workload so has a limited impact on the cognitive resources of the driver. The potential for this system is also supported by Wu et al. (2017) as it indicated pedal misapplication is more likely to occur if the driver previously had their foot on the accelerator pedal. This type of solution would require training for bus drivers as it would involve changing automated processes associated with driving. It should be noted that this was a small-scale pilot study and further research is required to explore the viability of brake toggling as an effective measure of mitigating pedal misapplication.

Existing technologies currently used by car manufacturers include Nissan's Emergency Assist for Pedal Misapplication. This system uses sonar, that is installed in the front and rear bumpers, to detect walls, vehicles, and other obstacles[15]. This means that if the accelerator is ever accidentally depressed rather than the brake pedal, the system warns the driver with an alert symbol and warning sound. It then prevents the vehicle from accelerating. This system also warns the driver if there is a risk of collision and automatically applies the brakes. Some models, such as LEAF, use information retrieved from the front camera of the car. This allows a greater detection of vehicles and pedestrians at a further distance. This can help prevent collisions caused by pedal misapplication up to 25 km/h. Further existing technologies include the Acceleration Suppression System introduced by Toyota as discussed in Section 1.1. Toyota created this new safety system to counter pedal misapplication after Toyota reported that "the number of fatal accidents involving drivers 75 or older in Japan doubled from 381 in 2007 to 791 in 2019"[16]. This technology uses existing hardware and relies on new software to judge when a driver may use the accelerator pedal instead of the brake. When the system detects obstacles (using Intelligent Clearance Sonar) the Acceleration Suppression System applies the brakes. This system works in a range of 0-30 km/h and can be retrofitted to existing cars. Toyota reported that by combining the Intelligent Clearance Sonar and the new Acceleration Suppression function, pedal misapplication collisions can be further reduced. Although these systems only activate at low speeds, additional advancements to pedal misapplication mitigations systems are expected to be developed in the coming years.

3.5 Limitations

There were a number of limitations identified during this review process. The main limitation that was identified was a lack of accurate and representative pedal misapplication data. Pedal misapplication data relies on the narratives of drivers and witnesses, which is prone to bias and errors in recall. This is especially the case for drivers who are unlikely to admit being the cause of pedal misapplication related incidents. This is evident in the media articles discussed in Section 1.1 as drivers will often claim their foot was on the correct pedal and the vehicle was at fault. It is also difficult to identify incidents related to pedal confusion as the driver could experience foot misplacement rather than confusion. There was also a lack of representative data as most studies reviewed were conducted in North America and Asia. Many of the studies identified used collision data from just North Carolina. This means that multiple reports (Schmidt and Young, 2010; NHTSA, 2015; Smith et al., 2021; Collins et al., 2014) have used the same or similar data in their studies. This could mean that the evidence used in this review only represents driving behaviour in North Carolina, as

[15] https://www.nissan-global.com/EN/INNOVATION/TECHNOLOGY/ARCHIVE/PEDAL/

[16] https://europe.autonews.com/automakers/toyota-will-roll-out-new-pedal-misapplication-safety-feature

there are universal differences in driving behaviour and road conditions which may impact pedal misapplication. It should also be noted that a large proportion of drivers in the USA drive automatic vehicles. This could also impact the frequency of pedal misapplication incidents, because some studies have discussed how most cases of pedal confusion occur within automatic transmission vehicles. The same can be said for those studies based in specific regions in the Republic of Korea (Lee and Lee, 2022) as their driving conditions and behaviours are expected to be different to that of the UK. Therefore, results from these studies may not be generalisable or applicable to the UK. Further research is needed in real-world settings within the UK to better understand the magnitude of the problem associated with pedal misapplication as well as the characteristics of crashes and drivers.

Further limitations for these studies included the methods used, such as the use of simulators. Although simulators enable the researcher to programme a controlled and replicable environment, the conditions participants are in are not necessarily reflective of everyday driving. The validity of findings from such simulator studies in relation to the topic of pedal misapplication arguably warrants further investigation. There are also limitations associated with driving tasks that take place in real world settings as participants are often monitored using cameras. Although this is a more naturalistic method, participants often change their behaviour when they know they are being observed.

In summary, these limitations must be considered when attempting to draw conclusions from this review. However, it is still clear that pedal misapplication is a demonstrable issue among drivers, having caused considerable incidents on roads. As such, further investigation is more than warranted and future studies should seek to consider and overcome the limitations noted here as far as is possible.

3.6 Summary

The main findings of this review include that pedal misapplication occurs not only during initial start-up and low-speed parking manoeuvres but also throughout the entire driving cycle. Pedal misapplication impacts all drivers. However, there may be certain risk factors more associated with the pedal misapplication collisions such as old age, cognitive impairment, small stepover pedal configuration, incorrect foot positioning, hesitant braking, short stature, smaller shoe size and possibly being female. It should be noted that there may be an issue with gender being a risk factor as females are more likely to be shorter in stature and have smaller shoe sizes, thus this relationship should be examined for further clarity. Issues with the academic research on this topic includes the bias towards using data from the US. Automatic transmission vehicles are far more popular in the US so we cannot make inferences for the UK which has a much higher proportion of manual transmission vehicles. It would be beneficial for future research to be conducted using data from both automatic and manual transmission vehicles to examine if automatic vehicle drivers are indeed more at risk than manual drivers.

Mitigation systems are growing in popularity amongst vehicle manufacturers. This is an extremely positive development. However, further examination of the systems highlighted in Section 3.4 is needed to clarify which is the most promising system for reducing collisions caused by pedal misapplication and further examination into the cause of pedal misapplication is needed to eradicate the issue all together.

4 Results: Crash Data Analysis

At the time of analysis, the RAIDS database contained 2321 cases. Within the database, 43 (2%) applicable pedal misapplication cases were identified. In 42 cases, the vehicle that experienced the pedal misapplication was a car, the remaining case was a light goods vehicle. 93% (2164) of the cases in the RAIDS database involved at least one car or light goods vehicle.

In total, 95 road users were involved in the 43 identified cases. 43 were drivers of the pedal misapplication vehicles, and 14 were passengers within these vehicles. The remaining 38 were other involved road users, with 8 of these being vulnerable road users (1 pedal cyclist, 1 motorcyclist and 6 pedestrians).

4.1 Crash characteristics

74% of the pedal misapplication collisions occurred in an urban environment and 72% on a 30 mph road. 7 of the cases occurred at night (1 without streetlights) and 7 cases had a wet road surface, all cases had good visibility and the weather conditions are not considered to have a direct contributing factor in any of the 43 cases. Out of all 43 cases, 4 were commuting and 1 was driving for work. All others were using the car for private or unknown reasons.

In 91% (39) of the cases, the pedal misapplication occurred prior to any impact; however, in 4 of the 43 cases, the driver had pedal misapplication after the initial impact, going on to have further impacts due to the pedal misapplication. In these cases, the shock and panic caused by the initial impact is likely the primary reason for the subsequent pedal misapplication.

4.1.1 Type of pedal misapplication

The 43 cases involved misapplication of the vehicle's pedals, either by the incorrect pedal being depressed for various reasons or prolonged application of the accelerator pedal while in the incorrect gear.

Figure 1 shows the type of pedal misapplication error within the sample. In most cases (29, 67%) where the incorrect pedal is depressed, the driver accelerates instead of applying brakes; in 1 instance, the clutch is depressed rather than the brake, and in another instance, the brake is depressed instead of the accelerator. In 4 of the cases, the driver's foot is initially applied to the brake but slips off onto the accelerator; one of these cases was due to wet footwear/pedals due to wet weather conditions prior to them entering the vehicle.

The remaining 8 cases occur where the driver chooses the incorrect gear accidentally and press acceleration pedal. These 8 collisions were not directly caused due to pedal confusion; however, in those instances, drivers failed to correct their actions, continuing to accelerate in the wrong direction for a prolonged duration, leading to a collision. 4 of the drivers selected 'Drive' or 1st gear instead of 'Reverse', 3 selected 'Reverse' instead of 'Park' and 1 selected 'Drive' instead of 'Park'.

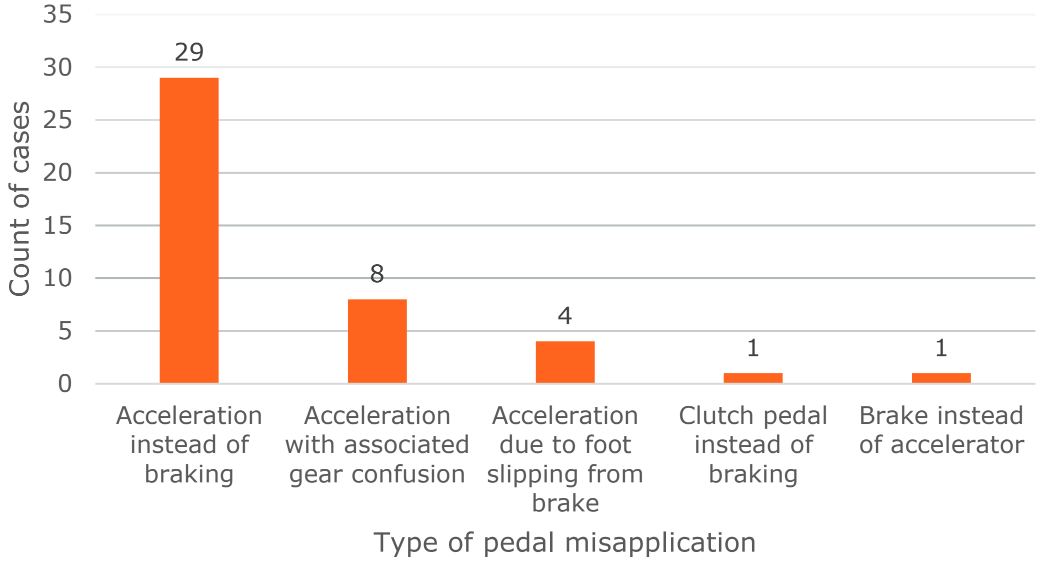

Figure 1: The number of cases for each type of pedal misapplication

4.1.2 Road type

28% of the pedal misapplication crashes occurred in parking lots or driveways, and 72% occurred on roadways. 29% of the cases occurring on roadways were at non-intersection locations, and 71% were at intersection-related locations Figure 2.

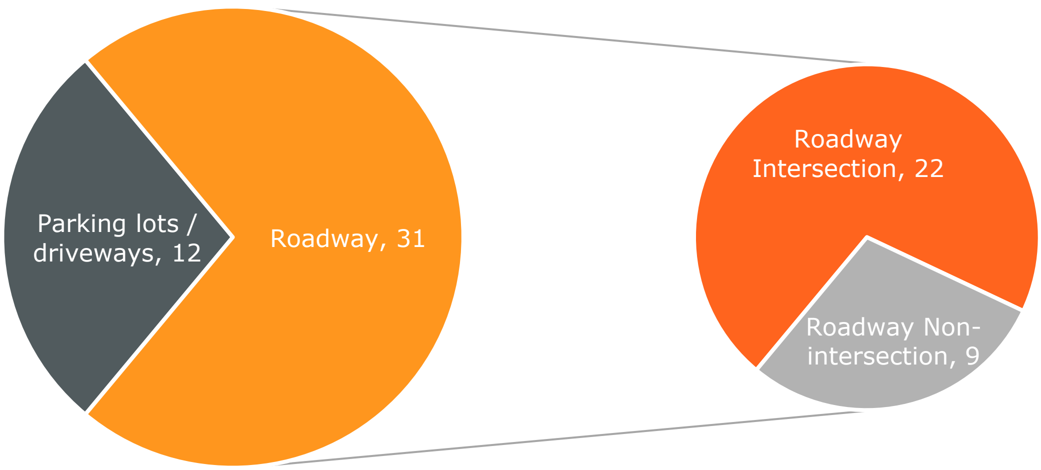

Figure 2: Number of pedal misapplication cases in parking lots and driveways verses roadways, with roadways split between intersections and non-intersections

Of all the RAIDS cases, involving cars and lights good vehicles, 33% occurred on A class roads, with 29% on C-class / Unclassified/ Car Parks/ Driveways. However, from Figure 3 it can be observed that pedal misapplication cases tend to take place on C Class/ Unclassified (17, 40%) and Carparks/Driveways (12, 30%) where vehicles are likely to be moving slower and/or manoeuvring.

68% of the RAIDS cases involving cars and vans are on single carriageways which would reflect the high occurrence (81%) within the pedal misapplication cases that occurred on a roadway. Dual carriageways (13%) and roundabouts (6%) are also seen within the pedal misapplication cases which occurred on a roadway.

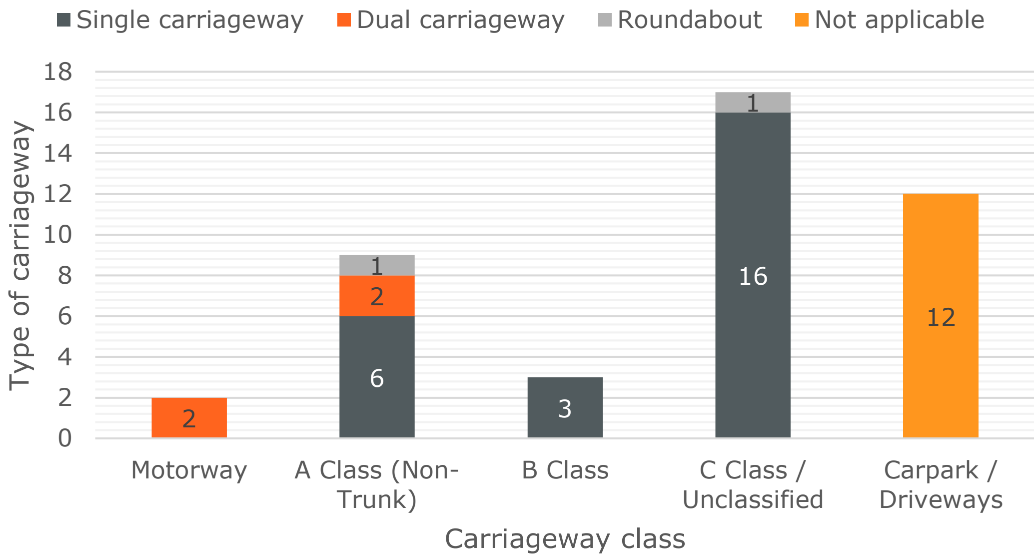

Figure 3: The number of cases which occurred on each carriageway class and on each type of carriageway

4.1.3 Pre-crash manoeuvre

12% (5) of pedal misapplication crashes occurred when drivers were going along (either straight or around a bend), 23% (10) occurred while stopping and further 21% (9) while moving off. 16% (7) occurred while carrying out turning manoeuvres including U-turns, three point turns and turning into a side road. The highest percentage of drivers (28%) were performing parking manoeuvres when the pedal misapplication occurred Figure 4.

18% (8) of the pedal misapplications occurred during the normal driving cycle, 40% (17) occurred at the end of the drive cycle, and 18, (42%) of cases occurred at the start of the driving cycle.

Pedal misapplication while parking can occur either at the start or end of the drive cycle, depending on whether they are pulling away from a parking space or coming to a stop while parking. Pedal misapplication while turning can occur during a normal driving cycle, at the start, or end of the drive cycle, influenced by the turning manoeuvre such as a three-point turn, U-turn or turning at a junction.

Five of the vehicles conducting a parking manoeuvre accelerated in reverse and had associated gear confusion, and all other vehicles suffered pedal misapplication whilst moving forward.

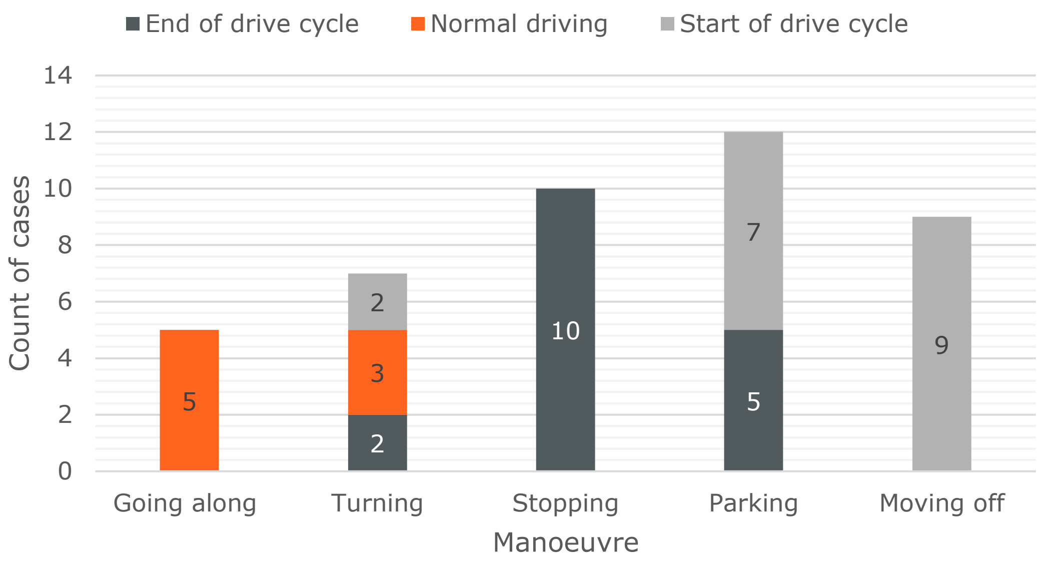

Figure 4: Pre crash manoeuvre when the driver suffered from pedal misapplication

Definitions:

Term	Definition
End of drive cycle	Coming to, or intending to come to, a complete stop, either intending to park or within the journey, for example at traffic lights.
Normal driving	Driving at a constant speed, or braking without intending to come to a stop, or accelerating whist already moving forwards.
Start of drive cycle	Starting to drive after the vehicle has been stationary, either after being parked or within a journey, for example after waiting at traffic lights.
Going along	Travelling along a road, either straight or around a bend, with no intention or reason to brake, or accelerate, harshly.
Turning	Any turning manoeuvre including a U-turn, three-point turn or turn off the main carriageway.
Stopping	Stopping on approach to a junction, for queuing traffic or after initial impact.
Parking	Any parking manoeuvre including entering or exiting a parking space in either a carpark, driveway or designated on-street parking
Moving off	Emerging from a junction, either give-way or traffic light controlled.

4.1.4 Collision type

Both cornering and manoeuvring had 11 cases each (26%) recorded, being the joint most frequently coded collision type (Figure 5). Crossing (vehicles turning) accounted for 12% (5 cases) with the top three collision types all involving some aspect of turning / manoeuvring and accounting for 63% overall. A further 5 cases were recorded as rear-end collisions, both pedestrian collision and loss of control was coded for 3 cases each and crossings, which did not involve turns, was coded for 2 cases. One case had the collision type of head on, and one involved merging and the final case was coded a miscellaneous.

All 3 pedestrian collision type cases involved a parking pedal misapplication vehicle. Ten of the 11 manoeuvring cases were parking or turning with remaining case stopping. The 5 cases which were crossing with a turning vehicle involved a pedal misapplication vehicle which was moving off (3) or stopping (2). The cornering vehicles were split between moving off (4), stopping (2), turning (3), and going along (2). Four of the 5 rear ends were stopping with one going along. Loss of control had a case each parking, turning, and going along. Crossing without turns involved one vehicle moving off and one stopping. The merging collision had a vehicle moving off, the head on collision was going along and the miscellaneous parking (Figure 5).

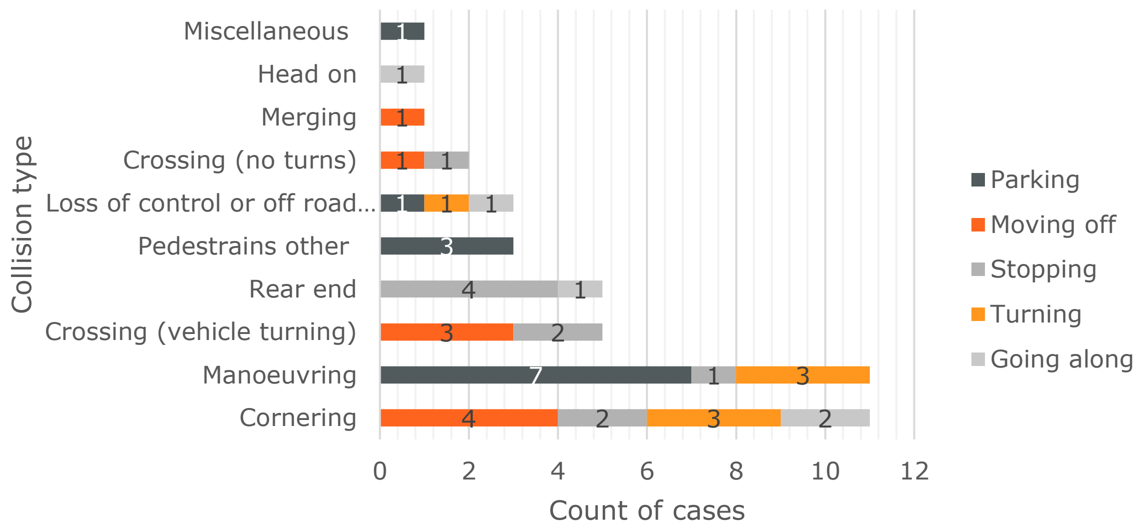

Figure 5: Number of cases for each collision type split by manoeuvre

4.1.5 Collision partners

Twenty-three (54%) of the pedal misapplication cases are single vehicle crashes, 5 of these involved unoccupied vehicles, with 8 parked vehicles in total. The remaining 20 cases involved one or more occupied vehicles or pedestrians. Over these 20 cases, 14 occupied vehicles, 1 motorcyclist, 1 pedal cyclist, 6 pedestrians and 3 unoccupied vehicles were involved. The highest frequency of other vehicles were cars. A total of 33 collision partners including all occupied and unoccupied vehicles, and pedestrian were involved (Figure 6).

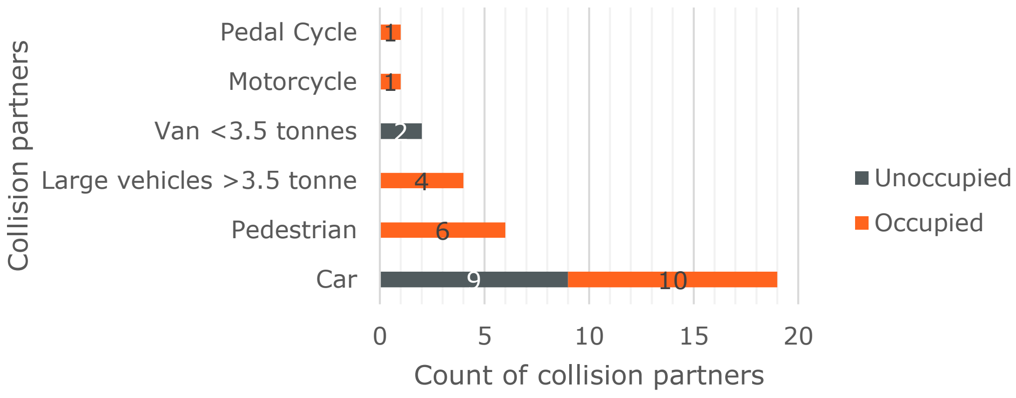

Figure 6: Number of each type of collision partner, both occupied and unoccupied, involved in the 43 pedal misapplication cases

4.1.6 Most significant impact

The most significant impact is with the object most likely to cause injury to any of involved road users. The most significant impact that the pedal misapplication vehicle was involved in was analysed. Fifteen pedal misapplication vehicles (35%) had the most significant impact into a wall/building. Most of these (13/15) were single-vehicle cases. It has to be noted that when multiple vehicles are involved, it is not always the other vehicles which causes the most severe impact to the pedal misapplication vehicle. For 25% of the pedal misapplication vehicles, the most significant impacts involve striking roadside furniture, including trees, fences/ barriers and road signs. In the remaining 40% of cases, the most significant impact of the pedal misapplication vehicle involved another vehicle, including pedestrians (Figure 7). The majority of most significant impacts are into objects which would likely cause the pedal misapplication vehicle to come to a stop, so the greater the collision speed the more severe the injures, with the exception of pedestrians, who often suffer serious injuries even during relatively low speed collisions.

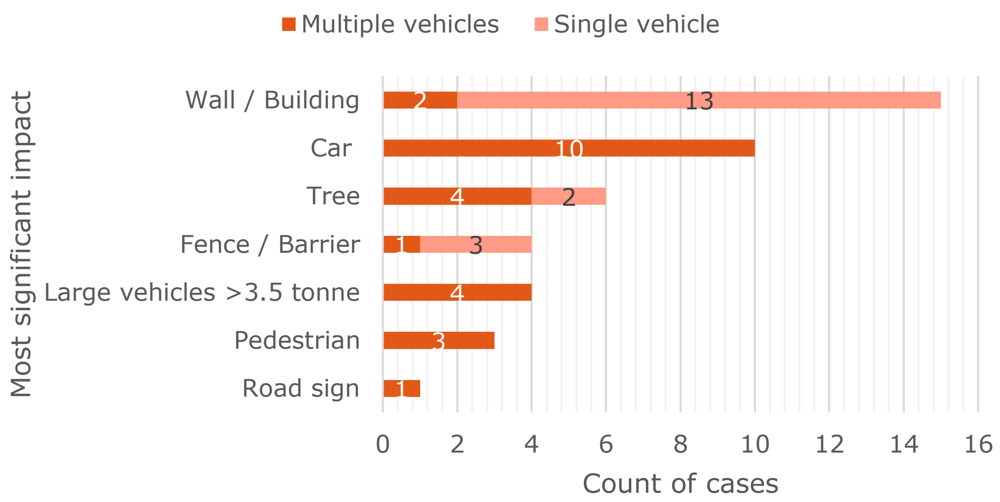

Figure 7: Number of cases for each object sustaining the most significant impact from the pedal misapplication vehicle, with single vehicle vs multiple vehicle collisions identified

4.1.7 *Impact speed and distance travelled prior to impact*

Figure 8 shows the distance travelled by vehicles due to pedal misapplication error and the impact velocity for each case. The majority of the cases had an impact speed of up to 35 mph (98%), with an average impact speed of 19 mph. Most vehicles were accelerated just before impact, suggesting that the vehicles were travelling at a relatively low speed when the pedal misapplication occurred.

In general, the distance the vehicle travels while the driver suffers from pedal misapplication ranges between a couple of meters to around 45 m. The average distance that the vehicles travelled was 23 m. In 3 cases, the distance travelled is considerably more significant, with a maximum distance of 141 m. In those instances, the driver continued to press the wrong pedal until the vehicle stopped after impacting with an object. This accounts for the large range in distances as the proximity of other vehicles, roadside furniture, the road layout and the vehicle's orientation and steering input will have an impact on how far the vehicle can travel before the impact. As most cases occur at a junction or in a car park/driveway and/or while manoeuvring, the vehicles are generally close to other objects.

The collision, which occurred at high speed (73 mph) over a long distance (141 m), was associated with a medical episode on a relatively straight 40 mph road. In this case, the vehicle accelerated over a long period to a high speed before finally having a head-on with an approaching vehicle as it drifted into the opposing carriageway.

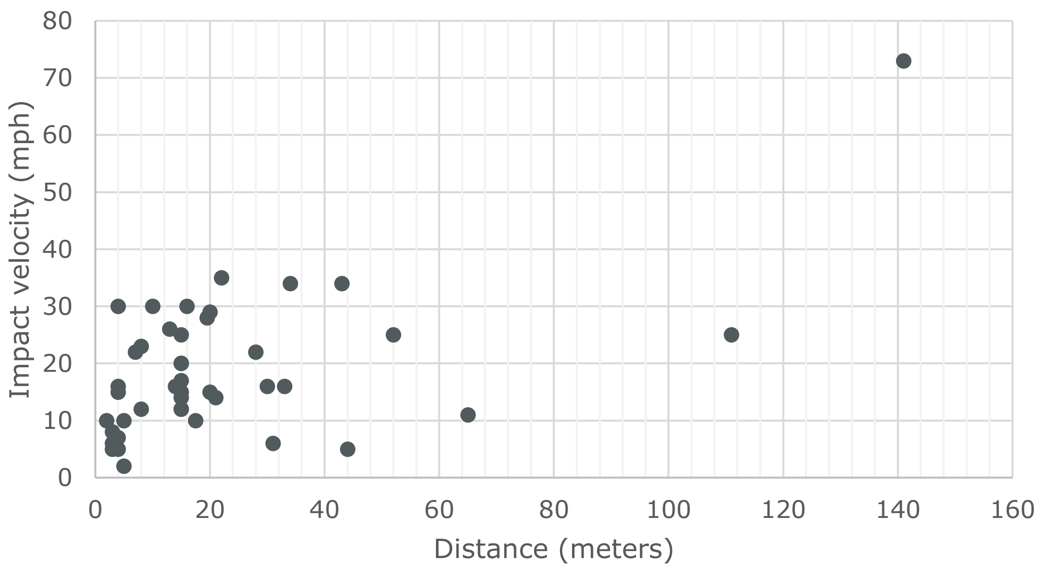

Figure 8: The distance travelled and the impact velocity for each vehicle suffering from pedal misapplication

4.2 Driver characteristics

4.2.1 *Age and gender*

Figure 9 shows the frequency of drivers who had pedal misapplication by gender and age category. Of all available RAIDS cases involving cars and light goods vehicles, 37% had a female driver. However, within the pedal misapplication cases, 67% of the driver were female (29 Female and 14 Male). One of the female drivers was noted to be of particularly short stature, sitting on a pillow and wearing high heels (Section 5.1).

74% of drivers of all RAIDS cases were less than 60 years old. However, in the pedal misapplication cases, only 40% of drivers were less than 60 years old (Figure 6). 51% of females and 71% of males were 60 years and above. The mean ages for pedal misapplication drivers were 61 years.

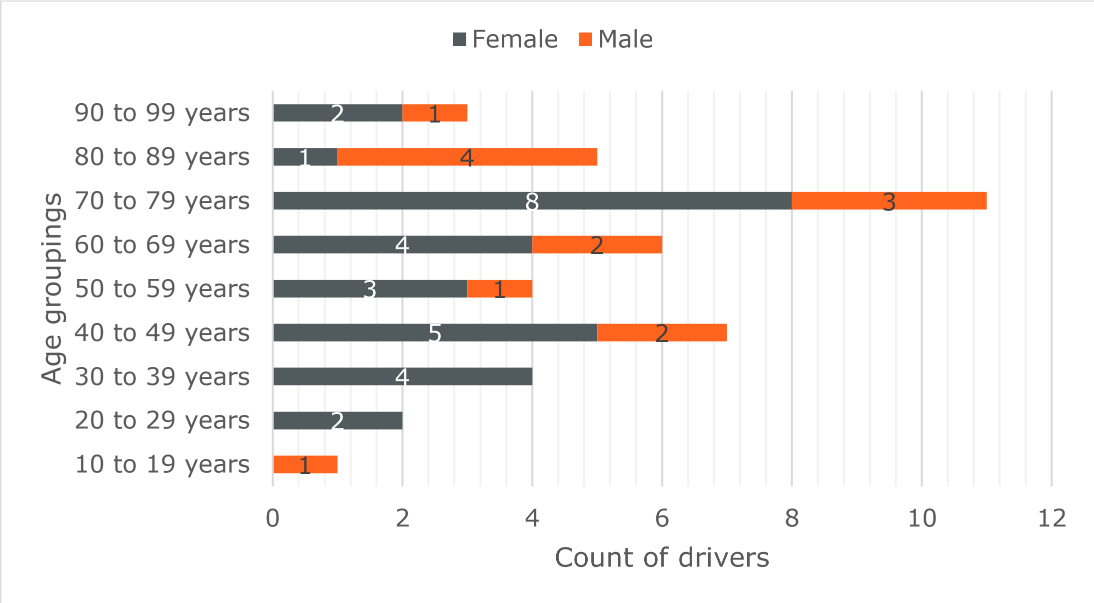

Figure 9: Number of drivers suffering from pedal misapplication by age bands and gender

4.2.2 Experience

Six of the drivers who were involved in a collision related to pedal misapplication were ‘learners’ (2 unaccompanied, 1 newly passed) and 7 were either known or believed to be unfamiliar with their vehicle (Figure 10). For at least one of the learners, it was also their first time in the vehicle. Two of those who were unfamiliar with the vehicle also had a possible medical episode at the time of the collision.

Four of the drivers who were under 40 years (57%) that suffered pedal misapplication were learners, while the majority (83%) of their elderly counterparts (over 50 years old) had no factors related to experience with either the duration they had held their licence or familiarity with the vehicle.

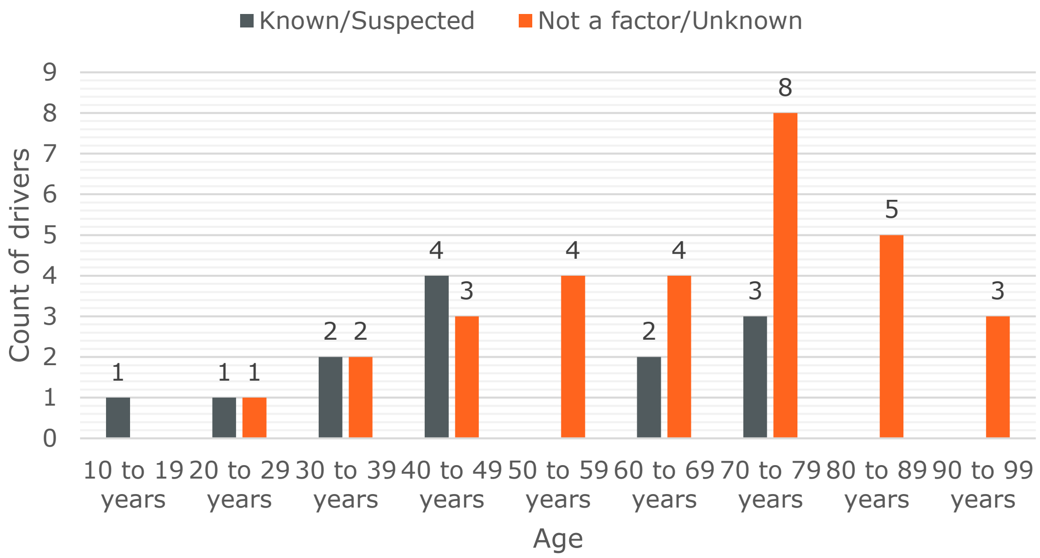

Figure 10: Experience as a contributory factor by age group

4.2.3 Impairment

Driver impairment accounted for 28% (12) of the pedal misapplication cases. The two main categories of impairment recorded were distracted driving and illness (Figure 11).

4.2.3.1 Distraction

Six drivers who had a crash associated with pedal misapplication were distracted. The driver, who was suspected of being distracted by an internal object, was approaching a queue when their foot slipped off the brake. The driver, distracted by an external object, was pulling out of a junction with a parked car obstructing their view until they initiated the manoeuvre.

The youngest two drivers who were recorded as being distracted by stress or emotional state of mind were learners (one who had just passed), who were likely nervous about learning to drive or driving unassisted. One did not look prior to pulling out and was impacted by an HGV, which caused them to panic, leading to pedal misapplication and further impacts. One of the elderly drivers, who was distracted by stress, had two passengers; they were trying to conduct a 3-point turn on a hill and likely felt under pressure to complete the manoeuvre and had selected the wrong gear.

4.2.3.2 Illness and drug-related impairment

Only one driver was impaired by alcohol or drug. They had a high dose of prescribed Oxycodone in their system, and it is associated with one of the Illness cases. Oxycodone at overdose levels can produce stupor, coma, muscle flaccidity, severe respiratory depression, hypotension and cardiac arrest. In another case, the driver of one vehicle had been having headaches for a couple of weeks before the collision and had recently had surgery on their right knee. Both drivers suffered fatal injuries from the collision rather than died from their medical illnesses.

The driver, in another case, experienced a bright flash on the dashboard just prior to the collision. Another driver had undergone chemotherapy the day before and was recovering from a recent hysterectomy. There was also a driver with ischaemic heart disease and previous myocardial ischemia, hypertension, and spinal osteoporosis. One driver suffered a stroke shortly after the collision and was likely feeling ill just before the collision.

All occasions of cases where the driver likely suffered pedal misapplication due to an illness had the potential to have lost consciousness for a brief period. Alternatively, in three cases, the driver could have been experiencing some leg pain or weakness, which could have caused the pedal misapplication. In four of these cases, the medical condition was pre-existing.

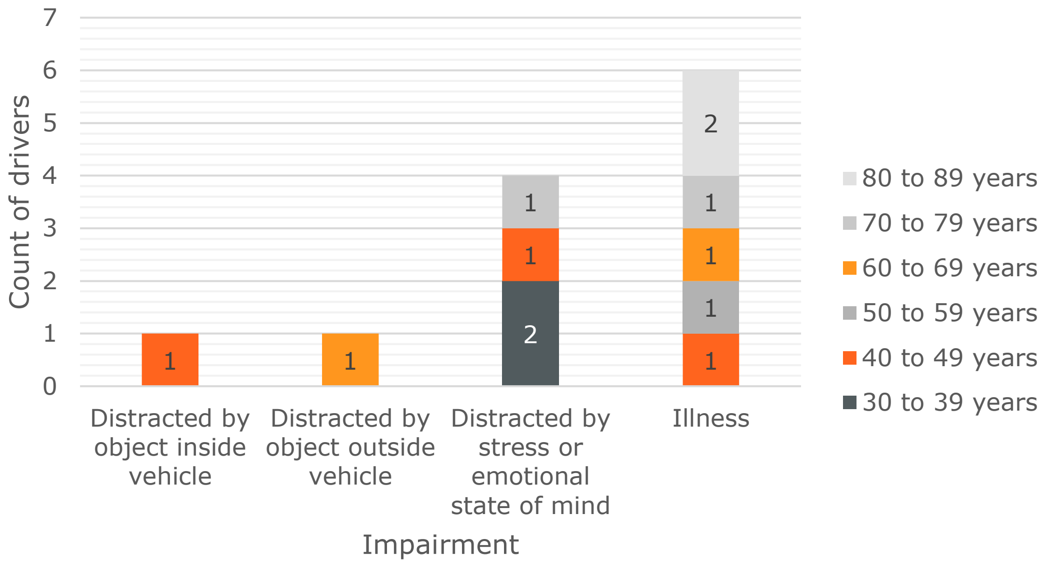

Figure 11: Frequency of drivers suffering from each impairment by age group

4.3 Vehicle characteristics

With the RAIDS database, out of all the cases involving cars and van, 51% were hatchbacks in comparison to 77% of the vehicles in pedal misapplication cases (Figure 12). There may be a like between the type of drivers that suffer from pedal misapplication (younger learner drivers and older drivers) and the type of vehicle these drivers favour.

70% of the vehicles which suffered from pedal confusion are 10 years old or older with 4 being around 20 years old. While this could suggest that older models are more susceptible to pedal misapplication, this could also be a consequence of the driver demographic, with younger and learner drivers favouring older, potentially cheaper, vehicles.

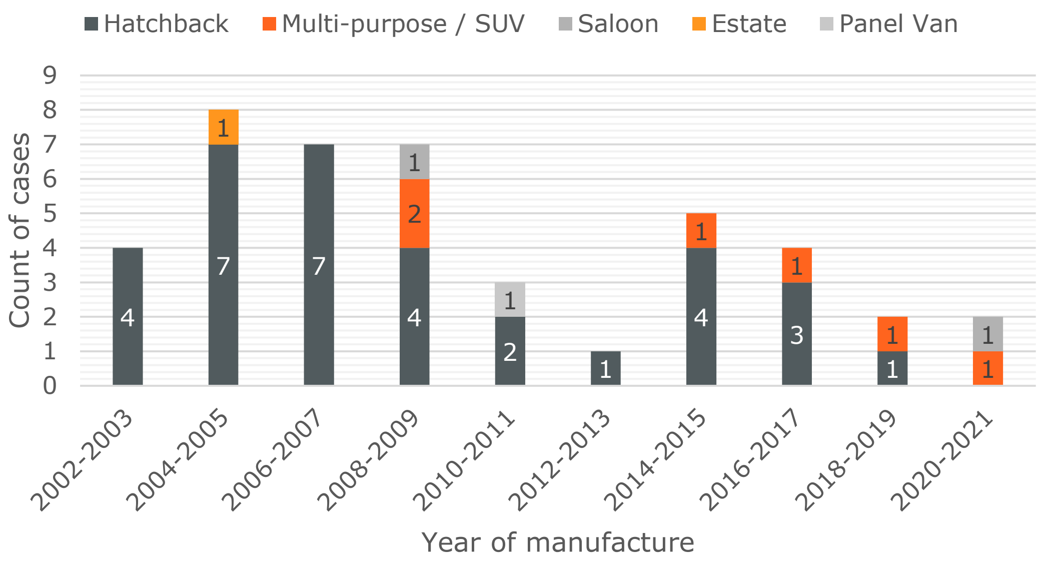

Figure 12: Frequency of misapplication vehicles by year of manufacture and vehicle type

4.3.1 Transmission type

With the RAIDS database, out of all the cases involving cars and vans, 24% were vehicle fitted with an automatic transmission, in comparison to 77% of the vehicles in pedal misapplication cases (Figure 13). This is a considerable indication that pedal confusion are more frequently associate with automatic transmissions than the manual transmission types.

Furthermore, 7 out of the 8 pedal misapplications with associated gear confusion are automatics, it would suggest that automatics are more susceptible to selecting the wrong gear.

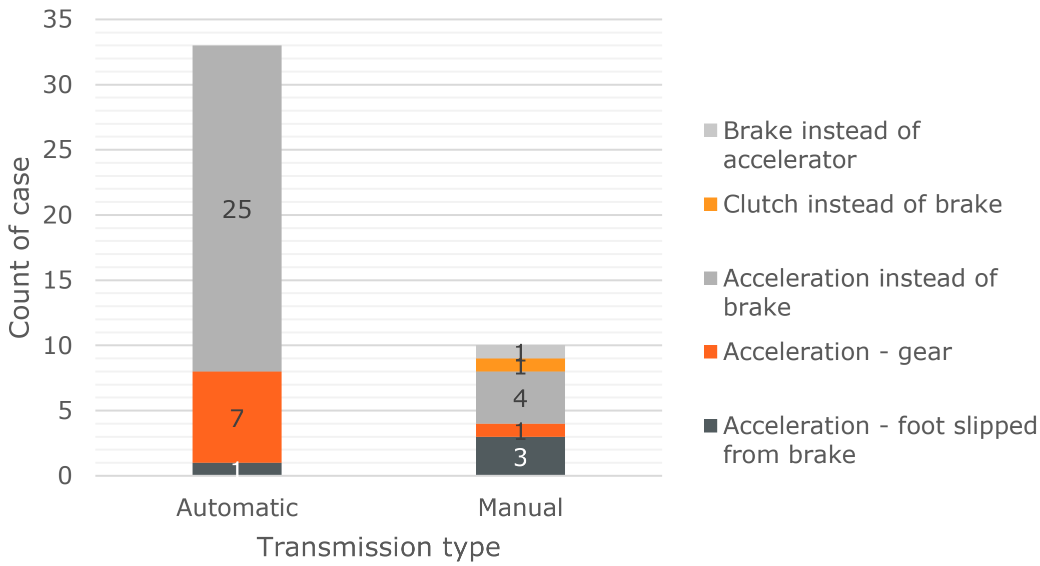

Figure 13: The number of pedal misapplication vehicles by transmission type and the type of pedal misapplication experienced

4.3.2 Drive type

With the RAIDS database, out of all the cases involving cars and vans only 3% were electric or hybrid vehicle type, which is reflected in the low numbers represented in pedal misapplication cases (Figure 14). As the number of these vehicles rise in the RAIDS database, it is expected that they will increase within the pedal misapplication cases as these vehicles are predominately automatic which has been shown to play a key factor in pedal misapplication cases.

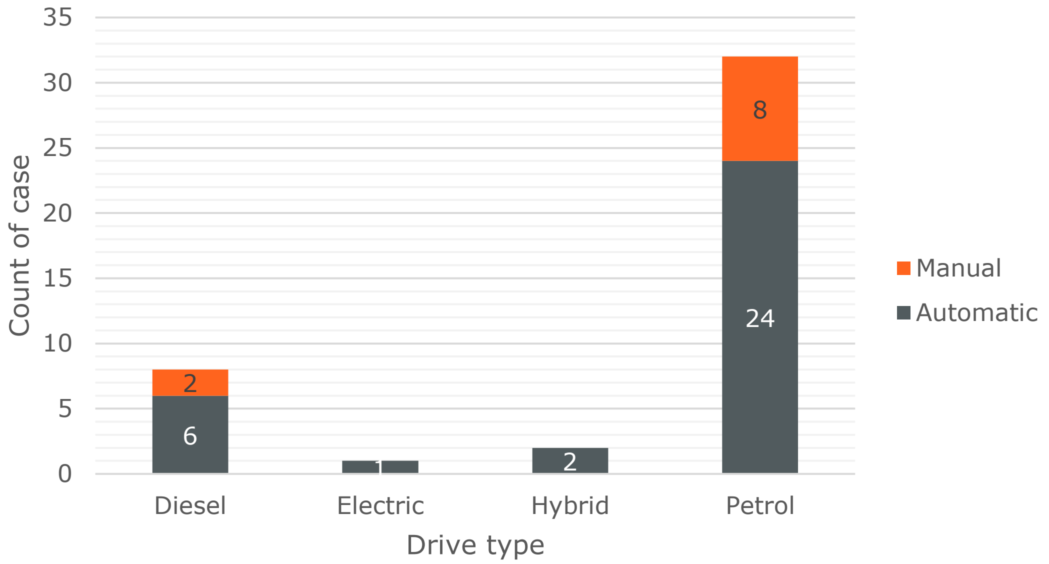

Figure 14: Number of pedal misapplication vehicles split by drive type and transmission

4.3.3 Other factors

No vehicles were recorded as having any modifications or any driver assistance systems active at the time of the collision. Five vehicles were noted as having slightly under inflated tyres; however, this was not found to be contributary in any of the cases.

4.4 Injury outcomes

Out of all the RAIDS cases involving cars and light goods vehicles, 10% were fatal collisions, 34% were serious, 41% slight, and 12% uninjured, in comparison to 5%, 26%, 42% and 28% respectively, for the collisions involving pedal misapplication. Therefore, pedal misapplication has a similar occurrence of slight severity cases but a more significant number of uninjured and a lower number of serious and fatal in comparison to all RAIDS cases.

Both fatal cases were associated with pedal misapplication due to a medical episode. In both cases, the cause of their death was due to the injuries sustained during the collision, with one having accelerated to high speed and the other impacting an HGV, rather than as a direct result of their medical episode.

4.4.1 Maximum Abbreviated Injury Severity (MAIS) by road user type

The MAIS represents the overall injury severity to an occupant. Of all the 95 individuals involved in the pedal misapplication cases, 53% (50) were uninjured. As shown in Table 3, 32 road users sustained MAIS level 1 injury, 5 individuals sustained injuries at MAIS level 2 and 7 sustained injuries at MAIS level 3 or greater. Vulnerable road users, including pedestrians, pedal cyclists and motorcyclists, were more likely to sustain an injury compared to other motor vehicles.

Table 3: The MAIS injury level of all road users involved in a pedal misapplication collision

Injury severity	Road user type			
	Occupant within the pedal misapplication vehicle	Occupant within other involved motor vehicle*	Vulnerable road users	Total
MAIS 1	18	12	2	**32**
MAIS 2	3	0	2	**5**
MAIS 3+	4	1	2	**7**
Unknown	1	0	0	**1**
Uninjured	31	17	2	**50**
Total	**57**	**30**	**8**	**95**

**not including motorcyclists which are included within vulnerable road users.*

4.4.2 Injury body location

Overall, the 45 individuals who were injured during a pedal misapplication collision sustained 134 separate injuries. Eighty-nine of these (66%) where injuries were at AIS level 1, 43 were AIS level 2+ and AIS level for two of the injury were unknown.

Of the AIS 1 injuries, the head (28%), right arm (13%) and left leg (13%) were the most injured, followed by the thorax (10%). Of the AIS level 2+ injuries, the thorax (33%) followed by the right leg (26%) most often sustained these injuries (Figure 15).

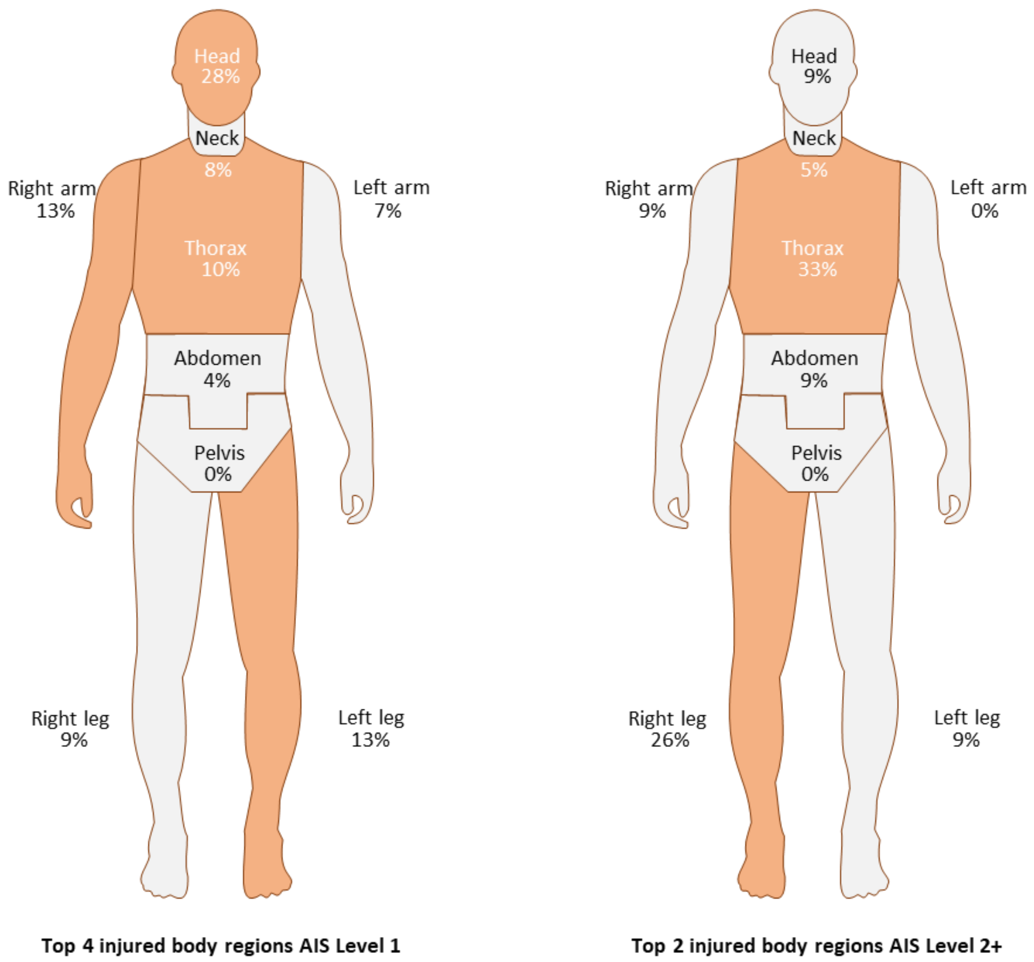

Figure 15: Injured body location by injury severity (AIS level 1 and AIS Level 2+)

5 RAIDS Case Studies

Three in-depth cases studies of particular interest which demonstrate key aspects of the highlighted factors associated with pedal misapplication are presented within this section. Table 4 gives a brief description of the identifying codes used within the case study 'Account of Collision' text. Within the text, the bracket after each identifier gives a brief description of the vehicle or occupant.

Table 4: Description of identifiers

Identifier	Description
V1	Vehicle 1, the vehicle suffering from pedal misapplication
V2	Vehicle 2, the other vehicle, impacted by V1.
V1O1	The first occupant of the vehicle 1. The first passenger of V1 would be V1O2 etc.
V2O1	The first occupant of the vehicle 2. The first passenger of V2 would be V2O2 etc.

5.1 Case Study #1

Collision Details:

Collision Type: Crossing – right turn, right side

Collision vehicles: Car v Car

Collision Severity: Slight

First Object Hit: Another vehicle

Most Severe Impact: Another vehicle

Type of Pedal Misapplication: Acceleration instead of Brake

Collision Environment:

Lighting: Daylight

Weather: Fine without high winds

Road surface: Wet/damp

Environment: Urban/Residential

Road Classification: A Class (Non-trunk)

Junction: T or staggered junction – give way

Speed Limit: 30 mph

Account of Collision:

This collision occurred in daylight hours with clear visibility, at a T-junction linking 2 single carriageway roads with a 30 mph limit. The road surface was damp. V1 (Toyota, Aygo, Car) was waiting at the give way line, with the intention of turning right onto the main road. V1O1 (adult, female, driver) has failed to look right before emerging into path of V2 (Ford, Focus, car) approaching on the main road from the right at 20-25 mph. V2O1 (adult, male, driver) had time to swerve to the right before the front nearside corner of V2 struck the front offside of V1. Post-impact, V1O1 put their **foot on the accelerator pedal instead of the brake**, causing the vehicle to cross the carriageway, mount the footway and impact a tree at low speed. V1 came to rest across the verge and footway, V2O1 brought the vehicle to rest further along on his path. V1O1 was restrained at the time of the impact and sustained minor injuries. V2O1 was suspected of being restrained and was uninjured. It is possible that the driver of V1 had looked right prior to V2 having exited from garage premises on the far side of the road located to the right 28 m from the point of impact. V1 may have misjudged that traffic from the pedestrian crossing located 37m to right on main road would not have reached her prior to making the turn.

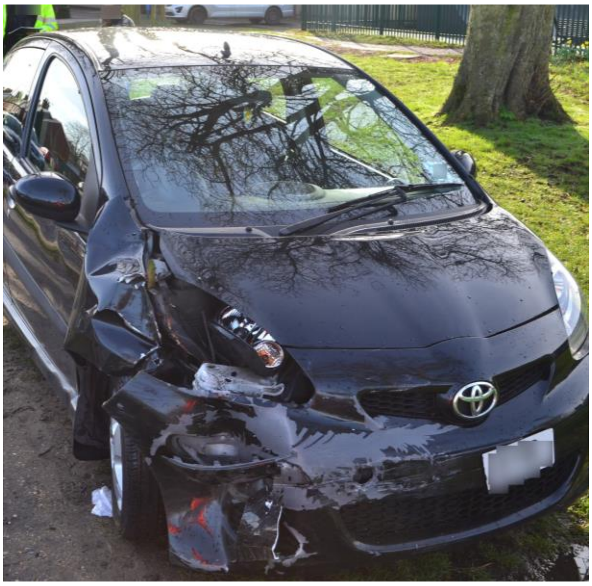

Figure 17: V1 (pedal misapplication vehicle) with damage to the front offside corner

Figure 16: The driver of V1 shown sitting on a pillow and wearing high heels

Vehicle:

Vehicle Type: Hatchback Car (7 years old)

Make/Modal: Toyota Aygo

Type of Transmission: Automatic

Modifications: None

Defects: None

Driver:

Age: 36

Gender: Female

Experience: Unknown

Impairment: Distracted

Medical / pre-existing: Unknown

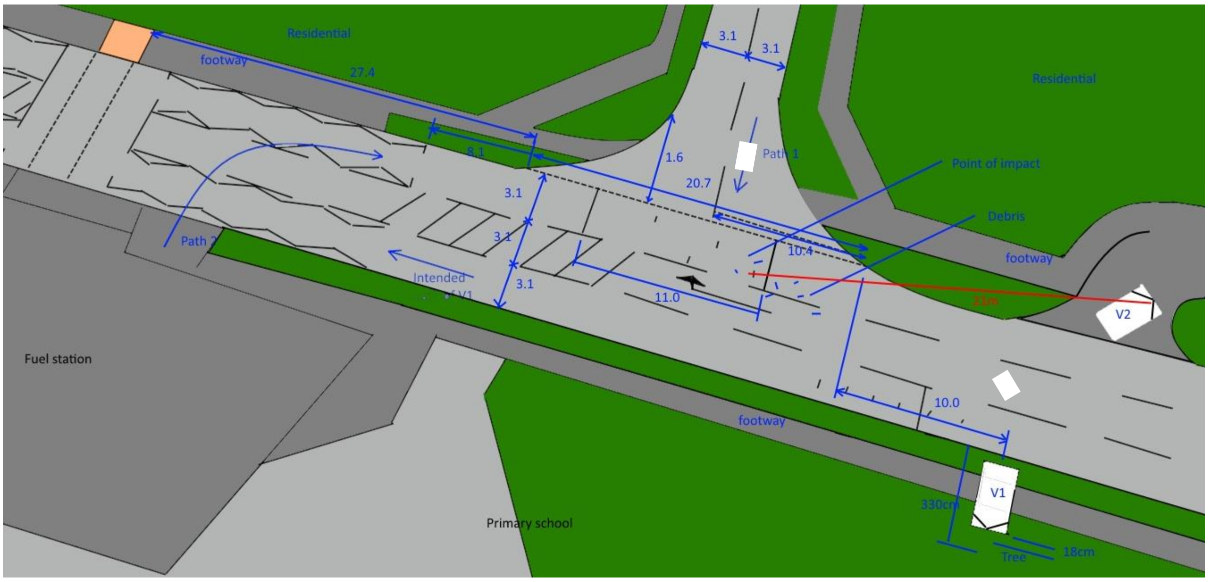

Figure 18: Scene plan with the path of V1 and V2, point of impact and final rest positions

Figure 19: V2 (other vehicle) with damage to the front nearside corner

Key Causation Factors:

- **Carelessness, thoughtless** – Known
- **Nervous or uncertain** – Suspected
- **Other personal factor** – Suspected
- **Distraction through stress or emotional state of mind** – Suspected
- **Failed to look** – Known
- **Other bad manoeuvre** - Known
- **Lack of attention** – Known

Key pedal misapplication observations:

Manoeuvre: Stopping after initial impact **(end of drive cycle)**

Timing: Pedal misapplication occurred **after** the initial impact with V2

Other: Driver of **particularly short stature, sitting on a pillow** and wearing **high heels**

5.2 Case Study #2

Collision Details:

Collision Type: Lost control or off road - other

Collision vehicles: Car (single vehicle)

Collision Severity: Damage only - Uninjured

First Object Hit: Building

Most Severe Impact: Building

Type of Pedal Misapplication: Acceleration instead of Brake

Collision Environment:

Lighting: Daylight

Weather: Fine without high winds

Road surface: Dry

Environment: Urban/Residential

Road Classification: B Class

Junction: T junction – auto traffic signal

Speed Limit: 30 mph

Account of Collision:

This collision occurred during daylight hours, in an urban area. The weather was fine without high winds and the road surface was dry. Visibility was good. At a T-junction of a B classified, single carriageway road, leading onto a unclassified road with a speed limit of 30 mph. V1 (Toyota, Yaris, Car) turned left from the main road just after an automatic traffic light controlled junction and entered a long downhill straight. It appears V1 clipped the nearside kerb before steering hard left over the kerb and footpath, colliding with a breezeblock outhouse located outside a residential premise. The vehicle knocked down the outer wall and came to rest half-way through the building with the vehicle fully across the footpath. V1O1 (adult, female, driver) and V1O2 (adult, male, front seat passenger) and V1O3 (child, male, rear offside passenger) were all restrained and uninjured. V1O1 was a learner driver, and this was the first time they had used an automatic vehicle; it is suspected that the driver **unintentionally accelerated when attempting to brake** when confronted by the hill which led to the initial loss of control.

Figure 20: V1 (pedal misapplication vehicle) with L plates having impacted a building

Figure 21: Automatic driving pedals within the footwell of V1

Vehicle:

Vehicle Type: Hatchback Car (4 years old)

Make/Modal: Toyota Yaris

Type of Transmission: Automatic

Modifications: None

Defects: None

Driver:

Age: 32

Gender: Female

Experience: Learner driver

Impairment: Unknown

Medical / pre-existing: Unknown

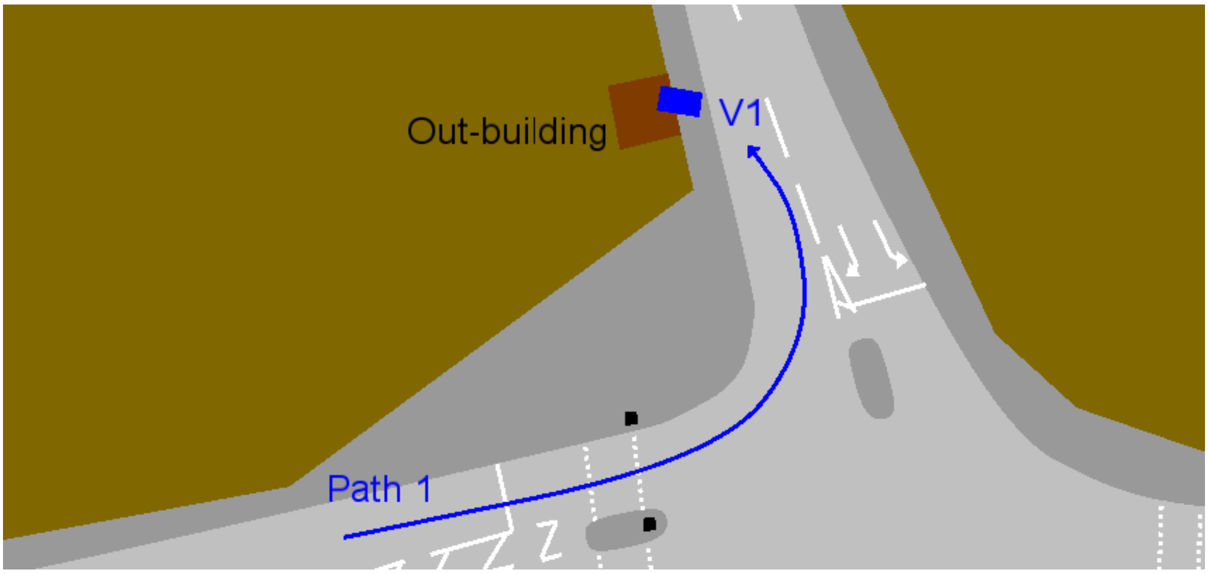

Figure 22: Scene plan with the path of V1 and final rest position

Figure 23: Path of V1 travelling downhill on a left hand bend

Key Causation Factors:

- **Carelessness, thoughtless** – Unknown
- **Nervous or uncertain** – Known
- **Error of judgment** – Suspected
- **Panic behaviour** – Known
- **Inexperience** – Known
- **Other bad manoeuvre** - Known
- **Control confusion: pedals/auto gearbox etc** - Suspected

Key pedal misapplication observations:

Manoeuvre: Going along (normal driving)

Timing: Pedal misapplication occurred before the initial impact with building

Other: First time use of an automatic vehicle and being instructed by family member

5.3 Case Study #3

Collision Details:

Collision Type: Manoeuvring – parking

Collision vehicles: Car v Forklift

Collision Severity: Slight

First Object Hit: Low fence

Most Severe Impact: Another vehicle

Type of Pedal Misapplication: Gear confusion – Drive gears selected instead of reverse.

Collision Environment:

Lighting: Daylight

Weather: Fine without high winds

Road surface: Dry

Environment: Urban/Commercial

Road Classification: C Class/Unclassified

Junction: Not at or within 20 m

Speed Limit: 30 mph

Account of Collision:

This collision occurred in daylight hours; the weather was fine without high winds. V1 (Toyota, Corolla, Car) was being driven by V1O1 (elderly, male, driver). V1 was preparing to exit a parking space they had driven front first into. After starting V1, **instead of reversing, V1O1 applied accidental acceleration (pedal confusion and automatic gearbox)** causing V1 to leap forwards, over the grass verge, through railings, over cycle lane, over raised pavement, onto one way street, facing the wrong direction. V2 (Manitou, MT625H, Forklift truck) was carrying a pallet of bricks on the forks at the front of the vehicle, and was on the one-way street already, travelling in the correct direction. V2O1 (adult, male, driver) reacts to V1 and comes to a stop and sounds the horn. V1 does not stop and impacts the stack of bricks and the front nearside tyre of the forklift. V1O1 claims to have been wearing a seatbelt but evidence suggests he was not (including a head strike to windscreen). V1O1 sustained minor injuries and was taken to hospital. V1O1 fails roadside eyesight test and has license revoked. V2O1 was uninjured.

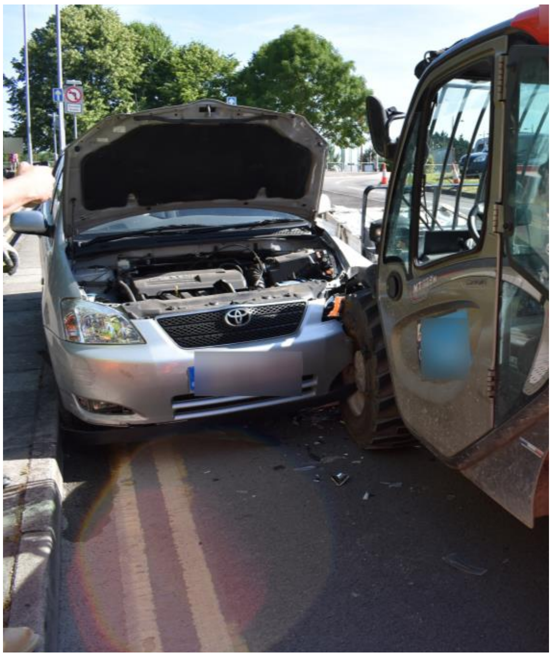

Figure 24: Impact configuration of V1 (pedal misapplication vehicle) and V2

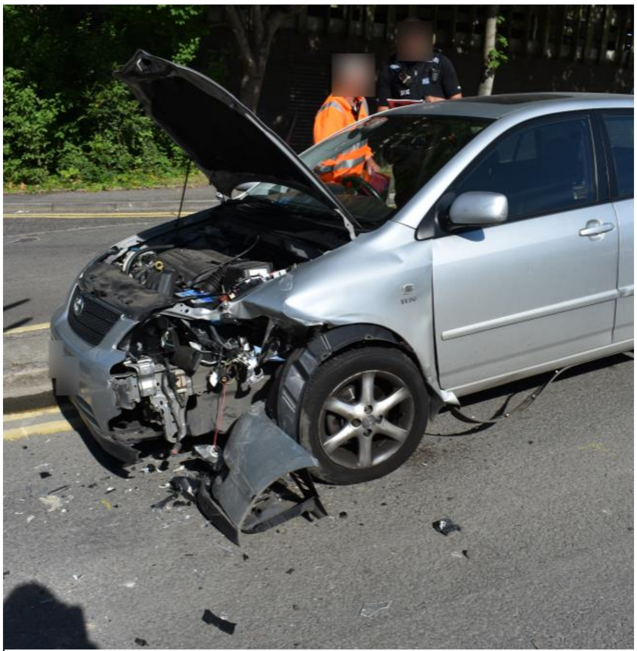

Figure 25: Damage to the front nearside corner of V1

Vehicle:

Vehicle Type: Hatchback Car (13 years old)

Make/Modal: Toyota Corolla

Type of Transmission: Automatic

Modifications: None

Defects: None

Driver:

Age: 92

Gender: Male

Experience: Unknown

Impairment: Unknown

Medical / pre-existing: Eyesight issues

Figure 26: Path taken by V1 who was parked in the bay occupied now by the blue vehicle

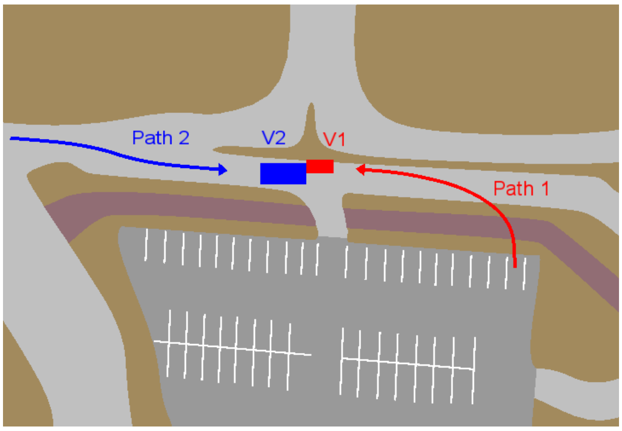

Figure 27: (left) Scene plan showing the path take by V1 and V2

Key Causation Factors:

- **Panic behaviour** – Suspected
- **Other personal factor** – Suspected
- **Other bad manoeuvre** - Known
- **Control confusion: pedals/auto gearbox etc** – Suspected

Key pedal misapplication observations:

Manoeuvre: Moving off after parking (start of drive cycle)

Timing: Pedal misapplication occurred before and continued after the first impact

Other: Elderly driver failed roadside eyesight test and licence revoked

6 Discussion

A systematic review of previous research found that several driver and vehicle related factors contribute to pedal misapplication resulting in a collision. To further understand this problem, in-depth data of real-world crashes gathered for the RAIDS from 2012 were analysed.

Around 2% (43) of the crashes within the RAIDS database were due to pedal application errors. Drivers involved in RAIDS pedal misapplication sample were characterised as more likely to be elderly than their crash counterparts. This finding concurs with earlier real-world studies conducted by Smith et al. (2021) and Lococo et al. (2021). Previous research has linked cognitive and functional impairments associated with ageing which delays reaction time for elderly drivers to regain control of the vehicle after the onset of pedal misapplication error (Gaspar and McGehee (2019)). This is an important factor to consider in collision avoidance because the proportion of people aged over 65 years to the population aged 15-64 years in Europe is projected to double between 2010 and 2050 (Lanzieri 2011). It is expected that the number of older people using passenger cars will be greater than ever before. If the predictions for the shift in population age distributions prove correct, there needs to be an active intervention through vehicle design and development and fitment of an appropriate safety system. The majority of RAIDS pedal misapplication collisions among drivers aged below 40 years (4 out of 7) tend to involve inexperienced drivers who do not hold a full driving licence.

From the analysis of RAIDS data, it is apparent that females were overrepresented in pedal misapplication crashes compared to their representation in all crashes in RAIDS, which is similar to the findings of Smith et al. (2021) and US Department of Transportation (2012). Males and females are physically different; females are on average shorter and have smaller foot sizes than males, potentially resulting in imperfect access to the pedals (Xi (2015)). Studies have predicted an increase in travel exposure (both licencing and travel miles) among females due to socio-economic changes and changes in driving behaviour (Romano et al. However, more research is necessary to identify which of these factors (being female or short stature) is more of a risk factor for pedal misapplication. Furthermore, studies have predicted an increase in travel exposure (both licencing and travel miles) among females due to socio-economic changes and changes in driving behaviour (Romano et al. 2008, Tsai et al. 2008). This implies that more emphasis is needed to develop active interventions to avoid pedal misapplication related crashes that were influenced by gender related factors.

A significant number of RAIDS pedal misapplication collisions occurred during turning (7) or parking manoeuvres (12) where there is a high chance of the head and body position being away from the ideal driving position (i.e., front/centre), which can also affect foot movement accuracy (Lococo et al. 2012).

Analysis of RAIDS pedal misapplication crashes indicated that 28% of the crashes occurred in parking lots and driveways, while roadways accounted for 72%, of which the majority (55%) occurred in a C class or unclassified road. The result suggests that crashes resulting from pedal misapplication tended to occur on smaller, lower-class carriageways or private parking spaces with lower speed limits compared to other crashes. The mean impact speed was 19 mph, suggesting that the vehicles were travelling at a relatively low speed when the pedal misapplication occurred. This was influenced by the nature of the pre-crash manoeuvre, how far the vehicle was accelerated before impact and the location of the crash.

The majority of the RAIDS pedal misapplications (about 49%) occurred at the initial start-up of the vehicle, followed by 33% occurring at the end of the driving cycle and the rest occurring during the normal driving cycle. These findings contradict the earlier assumption that pedal misapplications are associated only with the start of a driving cycle (Pollard and Sussman 1989 and Schmidt 1989).

In general, environmental factors such as visibility and weather were not observed to be particularly characteristic of pedal misapplication crashes, which is similar to the findings of Smith et al. (2021). However, in one of the cases, the wrong pedal was pressed due to the foot slipping because of wet footwear or a wet pedal. It was noted that some pedal misapplication occurs as a result of driver distraction, stress or recent trauma, and medical conditions. In the RAIDS pedal misapplication cases, driver distraction and illness accounted for 12 (6 each) cases.

Within the RAIDS database, vehicles fitted with automatic transmissions are more frequently associated with pedal misapplication cases. Further research is necessary to understand how the design of automatic transmission vehicles contributes to the likelihood of pedal misapplication, as the sales of those vehicles in the UK are significantly increasing. Only 3 cases associated with pedal misapplication were a hybrid/electric vehicle. However, it is important to consider that the increase in electric vehicles on the road and most of those vehicles are fitted with automatic transmission. Furthermore, EVs typically are able to accelerate much faster than the conventional internal combustion engine, providing less response time for making corrective actions when a pedal application error is committed.

Analysis of RAIDS data shows that the consequences of pedal misapplication crashes are relatively not severe compared to all crashes in the RAIDS database. Only 5% of those involved in a crash involving a pedal application error were fatally injured – but this figure for all RAIDS cases jumps to 10%. The majority of all road users associated with the pedal misapplication crash were uninjured (50 out of 95). The findings also suggested that whenever pedal misapplication leads to a collision involving vulnerable road users, the potential for sustaining serious injuries is high.

One of the limitations of this study is the available number of relevant cases within RAIDS database. It is important to note that the RAIDS case collection criteria biases collisions involving injuries and those which have taken place on a public road. Therefore, damage-only crashes (i.e., with no reported injury) and those that occurred solely in a private car park are underrepresented. Therefore, it is likely that many pedal misapplication cases did not meet RAIDS inclusion criteria and were not investigated. Furthermore, crash investigators mostly rely on occupant and witness statements and the type of manoeuvre the vehicle took before the collision. Combining those with analysing in-vehicle data such as EDR can benefit the identification of pedal misapplication more reliability.

This study has provided useful insights into collisions related to pedal misapplication. It shows the need for an advanced driver-assist system to detect and prevent collision due to pedal misapplication. There are systems available in the market that automatically suppress acceleration and apply brakes (Section 3.4); however, the real-world efficiency of those currently is not known. If those technologies are proven efficient in avoiding crashes or mitigating collision severity, then the fitment rate of those could be increased through rewarding points for those fitments in consumer test programmes such as Euro NCAP or through relevant standards that make the fitment of such systems mandatory.

7 References

Association for the Advancement of Automotive Medicine (AAAM, 2005). *Abbreviated Injury Scale 2005*. Barrington, Illinois, U.S.A. 2005.

Association for the Advancement of Automotive Medicine (AAAM, 1990). The abbreviated injury scale-1990. Des Plains.

Collins W, Evans L and Hughes R (2014). Driver brake and accelerator controls and pedal misapplication rates in North Carolina. National Highway Traffic Safety Administration.

Freund B, Colgrove LA, Petrakos D and McLeod R (2008). In my car the brake is on the right: Pedal errors among older drivers. *Accident Analysis & Prevention, 40*(1), 403-409.

Gaspar JG and McGehee DV (2019). Driver brake response to sudden unintended acceleration while parking. *Transportation Research Interdisciplinary Perspectives, 2.*

Hasegawa K, Kimura M and Takeda Y (2021). Pedal Misapplication: interruption Effects and Age-Related Differences. *Human Factors, 63*(8), 1342-1351

Ichiro O and Kazunori S (2015). Preventing accidents caused by unintended acceleration and subsequent continuous acceleration in automatic transmission vehicles. *Ono-fumimachigai.*

Kawai N and Nakata R (2022). Do older adults mistake the accelerator for the brake pedal?: Oder adults employ greater prefrontal cortical activity during a bipedal/bimanual response-position selection task. *Behaviour Brain Research, 432.*

Lee Y and Lee J. (2022). Report on pedal confusion in driving via forensic video*. Forensic Science International: Reports, 5.*

Lanzieri G. (2011). *The greying of the baby boomers*. Eurostat Statistics in focus.

Lococo KH, Staplin L, Martell CA and Sifrit KJ (2012). *Pedal application errors (No. DOT HS 811 597)*. United States. Department of Transportation. National Highway Traffic Safety Administration.

NHTSA (2015). *Driver brake and accelerator controls and pedal misapplication rates in North Carolina.* Report dated May 2015.

Pistak K, Edwards A and Huysamen K (2022). Pedal Application Error: Pedal Indicator Light – Human Machine Interface (HMI). *TRL.*

Pollard J and Sussman ED (1989). *An Examination of Unintended Acceleration*. Washington, DC: US Department of Transportation.

Pollard, J.K. (1989). An examination of sudden acceleration. National Highway Traffic Safety Administration. DOT HS 807 367.

Rogers N (2022). *Bus Safety Standard: Report – Pedal confusion.* Report dated August 2022

Romano E, Kelley-Baker T and Voas R.B. (2008*).* *Female involvement in fatal crashes: increasingly riskier or increasingly exposed?* Accident; analysis and prevention, 40(5), pp.1781–8.

Runham P, Stefanova T, Delamare L, Skippon S, Edwards A, Martin P and Helman S (2018). The Transport for London Bus Safety Standard: Pedal Application Error Prevention & Recovery. *TfL.*

Sager M (2003). *Alzheimer's Disease: Research Update*. Keynote Address, Annual Education conference, Alzheimer's Association Southeastern Virginia Chapter.

Schmidt RA and Young DE (2010). Cars gone wild: the major contributor to unintended acceleration in automobiles is pedal error. *Frontiers in Psychology,* 1, https://doi.org/10.3389/fpsyg.2010.00209

Smith CP, Sherony R and Gabler HC (2021) Identification and Charactertization of Pedal Misapplication Crashes Using National and State Databases. IRCOBI Conference Proceedings. 2021.

TfL (2022). *Bus Safety Standard Report – Pedal confusion*. Report dated August 2022.

Tsai VW, Anderson CL and Vaca FE. (2008). *Young female drivers in fatal crashes: recent trends*, 1995-2004. Traffic injury prevention, 9(1), pp.65–9.

Wu Y, Boyle LN, McGehee D, Roe CA, Ebe K and Foley J (2015). Modelling Types of Pedal Applications Using a Driving Simulator. *Human Factors and Ergonomics Society, 57*(7). 1276-1288.

Wu Y, Boyle LN, McGehee D, Roe CA, Ebe K and Foley J (2017). Foot placement during error and pedal applications in naturalistic driving. *Accident Analysis & Prevention, 99*. 102-109.

Xi Y (2015). Understanding the Automotive Pedal Usage and Foot Movement Characteristics of Older Drivers. Clemson University. TigerPrints All dissertations.

Pedal Misapplication Study

Pedal misapplication is when the driver applies the wrong pedal of a vehicle, for example: accelerating instead of braking. When followed by the inability to regain control, this can result in collisions, causing damage to vehicles, infrastructure, and potentially, fatal injury. Current figures of pedal misapplication occurrences are potentially underestimated as depends heavily on driver statements, which are often unreliable. As a result, investigators are reliant on other data sources such as camera footage and examining the vehicle controls to determine the cause of the collision. This study examined the characteristics of collisions related to pedal misapplication. A systematic literature review was performed to explore the topic of pedal misapplication. Previous research found that pedal misapplication can occur throughout the entire driving cycle and can impact all drivers. However, certain risk factors were identified, including; old age, cognitive impairment, small stepover pedal configuration, incorrect foot positioning, hesitant braking, short stature, smaller shoe size and possibly being female. The review also presented countermeasures, including technologies that are available in the market, which have the potential to mitigate collisions caused by pedal misapplication. In addition, real-world collision data (RAIDS) from 2012 were interrogated to identify pedal misapplication related collisions for further analysis. The majority of the analysed collisions were caused by the driver accelerating instead of applying brakes and a high proportion occurred on smaller roads or car parks at low speed limits, with just under 50% occurring at initial start-up. Within the sample, similar contributing factors were identified to those found in the literature. Elderly drivers and female drivers were most commonly involved with impairments of driver distraction and illness reported. Vehicles fitted with automatic transmissions were more frequently associated with pedal misapplication cases. This study provides useful insights about crash characteristics and contributory factors of collisions related to pedal misapplication. As crash mitigation systems are growing in popularity amongst vehicle manufacturers, the development and fitment of a system that can detect and mitigate pedal misapplication should be encouraged. This can be achieved through rewarding points in consumer test programmes or by making fitment mandatory through relevant standards.

Other titles from this subject area

PPR931	Pedal Application Error: Pedal Indicator Light - Human Machine Interface (HMI). Kolby Pistak, Alix Edwards & Kirsten Huysamen. 2022.
PPR984	The Transport for London Bus Safety Standard: Pedal Application Error Prevention & Recovery. Patrick Runham, Teodora Stefanova, Lise Delamare, Stephen Skippon, Alix Edwards, Phil Martin, Shaun Helman. 2022.

TRL
Crowthorne House, Nine Mile Ride,
Wokingham, Berkshire, RG40 3GA,
United Kingdom
T: +44 (0) 1344 773131
F: +44 (0) 1344 770356
E: enquiries@trl.co.uk
W: www.trl.co.uk

ISSN 2514-9652

DOI
https://doi.org/10.58446/omrt5829

PPR2015