Bus companies and roadworthiness:

an in-depth analysis of the factors influencing inspection and incident outcomes

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ABSTRACT

Bus roadworthiness is the premise of the provision of reliable and safe bus services. The roadworthy condition of Victorian buses, however, is less than satisfactory with approximately one fifth of the accredited buses identified as posing safety concerns during annual inspections. The adverse impacts of unroadworthy buses are substantial. Unroadworthy buses are prone to unexpected on-road breakdowns and fires, which delay and inconvenience passengers, impair service quality, potentially jeopardize public safety, and bring about productivity (e.g. downtime) and financial (e.g. damage) losses for bus operators.

This thesis aims to develop an in-depth understanding of the factors influencing bus maintenance, roadworthy, and safety performance in Victoria, Australia. Four research components were devised, as listed below.

First, a sophisticated approach was developed to establish a comprehensive understanding of the current bus inspection system and outcomes, at both individual and fleet level. Four patterns of inspection outcomes were identified (non-failure, lower-risk, high-risk and critical failure), demonstrating varying levels of likelihood and magnitude of failure during annual inspections. Four operator types were constituted, building on the compositions of failure patterns within the fleet, which acted as the baseline against which operators could benchmark their current fleet roadworthy performance.

This second research component evaluated the current self-reported inspection practices of Australian bus operators. The results revealed that pre-trip and mandatory, independent inspections were well acknowledged and widely conducted, with the recognition and implementation of time/distance-based inspections being weaker. Factors including operator size, location, service type, as well as perceptions regarding the importance of inspections, were found to influence inspection practices.

The third phase identified the factors contributing to roadworthy outcomes and quantified the effects attributable to vehicles and operators. Vehicle age, odometer reading, make and configuration all contributed

to inspection outcomes, as well as the size and location of the operators. Controlling for the influential factors, the level of inspection failure risk associated with individual operator types was presented.

The final study set out to extend the understanding of the impact of fleet roadworthy performance on fleet incident outcomes, in relation to other key operational characteristics. It was found that fleet size, location, and service type were associated with the risk of incident occurrence, and fleet roadworthy performance, age and travel distance with incident frequency. The results highlighted the different effects operational characteristics had on incident risk and prevalence.

To summarise, this thesis will make both theoretical and methodological contributions, including the realization of the overarching impact of fleet setting, the consequent application of robust modeling approaches, and the innovative and elevated understanding of fleet maintenance, roadworthy, and safety performance. The findings will directly inform practitioners in the bus industry (operators, inspectors, and regulators, etc.), helping to improve bus fleet operation and performance.

DECLARATION

This thesis is an original work of my research and contains no material which has been accepted for the award of any other degree or diploma at any university or equivalent institution and that, to the best of my knowledge and belief, this thesis contains no material previously published or written by another person, except where due reference is made in the text of the thesis.

Signature: [redacted]

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Date: …3 Sep, 2020…

PUBLICATIONS DURING ENROLMENT

The following publications have arisen from the research reported in this thesis:

Journal article

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Peer-Reviewed Conference Papers

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1.1 Introduction

Public transport systems are essential services to the liveability, sustainability, and equity of a city. Buses, as the feeders and distributors in the integrated network, are vital to the provision of a good public transport system. The essence of bus service, reliability, and safety, lay critical emphasis on vehicle roadworthy condition and therefore maintenance efficacy. This thesis aims to establish an in-depth understanding of factors influencing bus maintenance, roadworthy, and safety performance in Victoria, Australia. This chapter starts with a discussion of the background and motivation for the research focus, followed by a presentation of the research aim and objectives. It concludes with an outline of the thesis structure.

1.2 Research Background

1.2.1 The elevated demand for public transport in Victoria

Victoria has the second highest population density in Australia with more than 70 percent of the population living in Melbourne, the capital city (Population Australia, 2020). With its population expected to increase from 6.3 million (2019) to 10 million by 2050, Melbourne is projected to overtake Sydney as the largest city in Australia in the next few decades (Population Australia, 2020; Victoria State Government, 2016). The rapid population growth in Victoria and the densification of cities put significant pressure on the transport system as a whole. The number of trips across all forms of transport a day in Melbourne is projected to increase from 17 million in 2019 to more than 30 million a day by 2050 (Department of Transport, 2019). To support Victoria through this growth, the Victorian Department of Transport recognizes the importance of ensuring the provision of a safe, reliable, inclusive, and long-term sustainable public transport system (Public Transport Victoria, 2019). Indeed, transport authorities around the world have been improving and promoting public transport to encourage modal shift from private vehicles to public transport and therefore to cope with issues including congestion, efficiency, sustainability and pollution (Nieuwenhuijsen & Khreis, 2016; Redman, Friman, Gärling, & Hartig, 2013; Şimşekoğlu, Nordfjærn, & Rundmo, 2015).

With more than two thirds of Melbourne residents living within the service range of a bus, rather than other forms of public transport such as trams or trains, buses are recognized as the most accessible mode of public transport. As the feeder and distributor that complements trains and trams in the integrated public transport network in Victoria, they are the key to the overall performance of the public transport system (Stevenson & Burns, 2018). For these reasons, the Victorian transport authorities have been endeavouring to improve the coverage, frequency, reliability, and safety of bus service to retain and attract patronage (Public Transport Users Association, 2018).

1.2.2 Bus safety and roadworthy condition

Public transport is considered to be one of the safest forms of transportation with the risk of being killed or seriously injured in a bus, in particular, found to be several times lower than in cars (Chimba, Sando, & Kwigizile, 2010; Ibrahim, Fildes, Logan, & Koppel, In Press; Kelvin Chun Keong, 2017). This holds much promise for policies aiming to promote public transport. As an attractive attribute, bus safety has received increasing research interest and efforts.

Regarding the risk factors, much of the previous research addressing bus safety has focused on factors such as driver characteristics (e.g., driver age, gender, experience) and behaviour (e.g., sleepiness and fatigue, compliance), environmental conditions (e.g., road condition, time of day, weather) and vehicle factors (e.g. bus service type, condition, and bus age). Vehicle defects are acknowledged to have adverse effects on heavy vehicle safety and contribute to between 10 and 20 percent of heavy vehicle crashes (Gou, Clément, Birikundavyi, Bellavigna-Ladoux, & Abraham, 1999; Sabow, 1994). It is also agreed that heavy vehicles with defects are significantly more likely to be involved in crashes than properly maintained and fully functioning vehicles meeting the technical requirements (Blower, Green, & Matteson, 2010). Despite the evident effects of vehicle defects on safety, the roadworthy condition has rarely been taken into consideration as a risk factor for bus safety.

Buses, unlike private vehicles, are generally operated in a fleet setting. The literature on freight and other heavy vehicles in a similar setting has examined fleet safety performance and generated valuable insights regarding the organizational factors influencing the performance (Refer to Section 2.3.3 for details). With regard to the scope of bus safety research, existing research addressing bus safety has focused mainly on the region, road segment, route, or individual (incident/driver/vehicle) levels. There is a need to take the fleet setting of bus operation into account when examining bus safety performance.

1.2.3 Bus service and mechanical reliability

Service reliability—the capability of the transit system to adhere to schedules and maintain a consistent travel time—is of critical significance to both the provider (operators, government) and user (passengers). Reliability has been widely recognized as influencing users' experience and satisfaction, which in turn greatly impacts mode choice and loyalty, with unreliability noted as being primarily responsible for the unpopularity of buses among Melburnians (City of Melbourne, 2012; Stevenson & Burns, 2018). Reliability is also of importance to bus operators, impacting operating costs, system efficiency, service attractiveness, ridership and revenue (Abkowitz, Slavin, Waksman, Englisher, & Wilson, 1978; Chakrabarti & Giuliano, 2015; Cham, 2006; Diab, Badami, & El-Geneidy, 2015; Liu & Sinha, 2007; Ma, Ferreira, & Mesbah, 2013; Mazloumi, Currie, & Rose, 2010; Prashker, 1979; Redman et al., 2013; Saberi, Zockaie, Feng, & El-Geneidy, 2013).

Mechanical reliability, defined as the probability that the vehicle and its components will operate properly at any given time (Dhillon, 2006), is one of the key factors influencing overall service reliability (Prashker, 1979). High levels of mechanical reliability ensure the availability of vehicles to deliver the planned service, while an unreliable transit fleet has direct and substantial adverse impacts on the provision of service. For instance, unexpected on-road vehicle breakdowns (e.g. brake failure, wheel detachment, lights overheating) or fires (e.g. engine compartment, air conditioning unit) (Bus Safety Victoria, 2013, 2015a, 2015b, 2015c, 2015d) interrupt services, delay schedules, inconvenience and disgruntle passengers, and impair service reliability and quality. Impaired mechanical reliability also results in productivity (e.g. downtime) and financial (e.g. vehicle damage, emergency make-up service for replacement) losses for transit agencies (Chakrabarti & Giuliano, 2015; Cham, 2006; Nallusamy, Balakannan, Chakraborty, & Majumdar, 2015).

1.2.4 Fleet maintenance and roadworthy performance

Both the safety and reliability of bus services are heavily dependent on maintaining vehicle fleets in roadworthy condition (Rechnitzer, Haworth, & Kowadlo, 2000). Vehicle conditions progressively deteriorate with time and use, impairing roadworthiness (in the absence of adequate maintenance) (Canadian Council of Motor Transport Administrators, 2014; Naser & Hawas, 2012; Peck, Scott Matthews, Fischbeck, & Hendrickson, 2015; Tofany, 1982; Tomeh, Brady, & Skorupski, 2001). As a result of intensive usage, buses need to be inspected and maintained on a regular basis to stay roadworthy. Notwithstanding, previous research on bus maintenance and roadworthy performance has been limited, and preliminary. In addition, the majority of the previous studies investigating bus maintenance practices were conducted in North America, the operation and regulation environments of which are considerably different from those in Australia. Clearly, there is a need to gain further understanding of bus maintenance and roadworthy performance in the Victorian context.

1.3 Research Aim and Objectives

In response to the research needs and gaps identified above, this research aims to develop an in-depth understanding of the factors influencing bus maintenance, roadworthy, and safety performance in Victoria, Australia. To achieve the overall research aim, the following research objectives have been established:

1. To establish a comprehensive understanding of Victorian bus inspection outcomes;
2. To evaluate current inspection and maintenance practices of Australian bus operators;
3. To identify the contributing factors to bus inspection outcomes and quantify their effects; and,
4. To explore the effects of bus fleet roadworthy outcomes in relation to other operational characteristics on fleet safety performance.

1.4 Thesis Structure

This thesis is divided into three major sections. The first section (Chapters 2 and 3) covers the 'background and approach' of the research program. Section II (Chapters 4-7), 'results and interpretation', provides research outcomes and interpretations of the key findings. The final section (Chapter 8), 'discussions and conclusions', presents a synthesis of the research findings as well as a number of implications for future research and practice. Figure 1.1 presents the structure of the thesis, shows how research objectives are linked to the thesis chapters, and presents the focus of each chapter. The thesis comprises eight chapters including this introductory chapter. A description of each chapter follows.

Chapter 2 – Literature Review presents an overview of existing literature and a summary of the key findings. The review focuses on knowledge in the field including (1) bus service reliability and mechanical reliability; (2) risk factors for bus safety, as well as the contribution of vehicle defects to bus crashes; (3) bus maintenance management and the relevant research. It concludes with the identification of current knowledge gaps and research opportunities.

Chapter 3 – Research methodology, context, and data illustrates the overall research framework, including the study design and key research components adopted to achieve the research objectives. It also provides a description of the data collection and analysis methods for this research.

Chapter 4 – Investigating the roadworthy condition describes the development of a sophisticated statistical approach to establish a comprehensive understanding of the roadworthy condition of Victorian buses. By applying multilevel latent class analysis, meaningful subtypes of inspection outcomes and operator types are extracted and the explorative analysis builds up the respective profiles for them.

Chapter 5 – Examining the inspection practices of bus operators investigates the operational characteristics, inspection practices, and the perceptions of the three inspection types across Australian bus operators. Using a questionnaire and accompanying statistical analyses, the variation of current practices within the industry as well as the factors influencing inspection practices are examined.

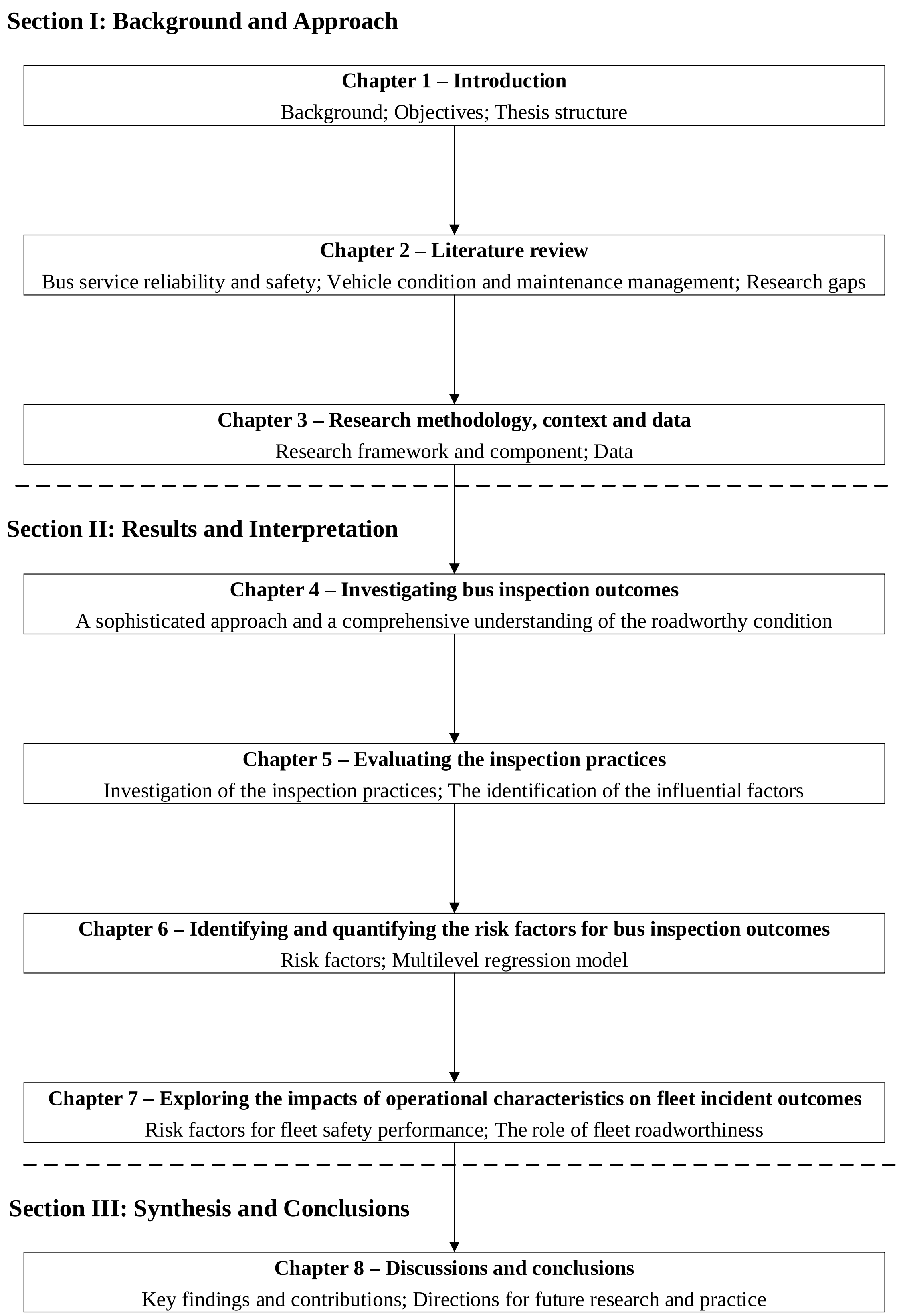

Figure 1.1 Thesis structure

Chapter 6 – Examining the risk factors for poor bus roadworthy outcomes focuses on identifying and quantifying the factors contributing to roadworthy outcomes. A three-level logistic regression model is formulated to model bus annual inspection outcomes with explanatory factors at the inspection, vehicle, and operator level. This chapter also evaluates the level of inspection failure risk associated with individual operators.

Chapter 7 – Exploring the impacts of operational characteristics on fleet safety performance extends the understanding of the impact of fleet roadworthy performance on fleet incident outcomes, in relation to other key operational characteristics. The negative binomial modeling framework is adopted to model the number of bus incidents. A particular focus of this chapter is the exploration of the most appropriate data structure and modeling approach.

Chapter 8 – Discussions & Conclusions concludes the thesis by providing a summary of the key findings that have emerged from the research and a discussion of the contributions to new knowledge, including both the theoretical and methodological inferences. It examines the impact of the findings on improved practices for both regulators and practitioners in Victoria to enhance bus fleet performance. It closes with a discussion of the limitations and some suggestions for future research in this field.

Chapter 2 LITERATURE REVIEW

2.1 Introduction

This chapter provides a review of the literature that addresses the relevant aspects related to bus roadworthiness. Both reliability and safety count on ensuring a high standard of vehicle roadworthiness, and this, in turn, is heavily dependent on maintenance. The review begins with an introduction to the significance of bus service reliability, with a specific focus on mechanical reliability. This is followed by an overview of the contribution of vehicle defects to bus safety performance, as well as other well-examined risk factors, including driver characteristics and behaviour, environmental conditions, and bus company operational characteristics (which has received little attention in the literature). Following this, the bus maintenance management system is illustrated, including the regime and the relevant aspects. This chapter concludes with the identification of knowledge gaps and the discussion of research opportunities.

2.2 Reliability and Vehicle Defects

2.2.1 Bus service and reliability

Public transport systems are essential services to the liveability, sustainability, and equity of a city (Diab et al., 2015). The recent rapid population growth in Melbourne, Victoria and the densification of cities (Department of Transport, 2019) have resulted in increased pressure on transport, which has seen transport authorities and agencies aspiring to improve the coverage, frequency and reliability of public transport service to retain and attract patronage (Public Transport Users Association, 2018).

Buses are the key to the provision of a good public transport system: they are the feeders and distributors in an integrated public transport network. They fill in gaps between train and tram routes and therefore have an impact on the performance of the whole public transport system (City of Melbourne, 2012). In addition, more than two thirds of Melbourne residents live next to bus routes rather than trains or trams (Stevenson & Burns, 2018).

Reliability, defined as the capability of the transport system to adhere to schedule, maintain regular headways, and consistent travel time, is one of the most important determinants of service quality (KFH Group, 2013; Liu & Sinha, 2007; Prashker, 1979). For service providers, reliability can help improve system efficiency, reduce operating costs, and increase ridership thus increasing revenue (Abkowitz et al., 1978; Chakrabarti & Giuliano, 2015; Cham, 2006; Diab et al., 2015; Saberi et al., 2013). For users, reliability is the foundation of the efficiency and attractiveness to using the transport system (Ma et al., 2013; Mazloumi et al., 2010; Redman et al., 2013) and has been shown to influence users' experience and satisfaction, which then greatly impacts mode choice and loyalty. Conversely, a lack of reliable services has been primarily responsible for the unpopularity of buses among Melburnians (City of Melbourne, 2012; Stevenson & Burns, 2018).

2.2.2 Mechanical reliability

Mechanical reliability, defined as the probability that the vehicle and the components will operate properly at any given time (Dhillon, 2006), is identified as the premise of reliability in a transport system (Prashker, 1979). Mechanical reliability emphasizes that vehicles allocated for service should be free from mechanical failures. Lack of mechanical reliability in a transit fleet has direct and substantial adverse impacts on the provision of reliable public transport service. For instance, unexpected on-road vehicle breakdowns (e.g. brake failure, wheel detachment, lights overheating) or fires (e.g. engine compartment, air conditioning unit) (Bus Safety Victoria, 2013, 2015a, 2015b, 2015c, 2015d) interrupt the service, delay schedules, result in uncertainty, inconvenience and disgruntle passengers and impair service reliability and quality. Impaired mechanical reliability also results in loss of productivity (e.g. downtime) and financial losses for transport agencies (e.g. through vehicle damage, provision of emergency replacement services, reduced patronage) (Chakrabarti & Giuliano, 2015; Cham, 2006; Nallusamy et al., 2015).

2.3 Safety Performance and Vehicle Defects

In addition to the implications on service reliability, vehicle defects during operation have the potential to comprise safety performance.

2.3.1 Vehicle defects contributing to crashes

Rechnitzer et al. (2000) conducted a review of studies in a number of jurisdictions (both domestic and international) which examined the role of vehicle defects in crash causation (crashes involving motorcycles and passenger cars). Significant variations were identified in the findings, but it was summarised that vehicle defects were a contributing factor in over 6 percent of crashes. Moodley and Allopi (2008) reviewed international studies using multidisciplinary crash investigation approaches and concluded that vehicle defects contributed to between 5 and 15 percent of crashes (without specific differentiation of vehicle class). According to Cuerden, Edwards, and Pittman (2011), vehicle defects were likely to be a contributory factor in around 3 percent of crashes (including motorcycles, passenger cars, and light vans but excluding heavy vehicles) in Great Britain.

Among the vehicle defects contributing to crashes (different terms including crash, accident, and incident have been used in the literature and crash will be used dominantly in this review), the most prevalent ones were related to brakes and tyres. van Schoor, van Niekerk, and Grobbelaar (2001) identified tyres and brakes as the two most dominant components that contributed to the mechanical defects causing accidents. Similarly, Cuerden et al. (2011) found that defective tyres and brakes were the most common contributory factors to crashes.

The literature also suggests that the effect of vehicle defects on crashes is greater for heavy vehicles (Paine, 2000). Grandel (1985) found that 6.4 percent of passenger cars and about 22 percent of commercial vehicles (bus and truck) involved in crashes displayed defects that contributed to the crashes. According to Sabow (1994), technical defects were considered to have a significant influence in approximately 8 percent of car crashes and 20 percent of heavy commercial vehicle crashes. Similarly, Gou et al. (1999) conducted a 2-year study on the effect of heavy-vehicle mechanical condition on road safety in Quebec, Canada, and found that mechanical defects were responsible for 10 to 20 percent of truck crashes.

It is also important to note that there is likely an under-reporting of the contribution of vehicle defects to crashes (when using police-reported crash statistics), mostly due to insufficient data availability and lack of expertise (Paine, 2000), which lead to a tendency to attribute incidents to human factors (Jakimovska & Duboka, 2015).

2.3.2 Risk factors for bus safety

Although considered to be a relatively safe means of transportation, bus-related casualty crashes and property losses are far from negligible (Evgenikos et al., 2016; La, Van Duong, Lee, & Meuleners, 2017). As a result of the number of injuries and fatalities as well as high media exposure following mass casualty bus crashes, there has been an increasing national and international interest in understanding the factors contributing to bus crashes. Much of the research has approached bus safety on various levels, including the region (e.g. state), route, road segment, or individual (incident/driver/vehicle) level. Table 2.1 provides a brief summary of the risk factors identified in these studies.

The majority of studies focused on driver characteristics and behaviour, environmental conditions, with very few addressing vehicle factors. Vehicle factors were usually examined in terms of their implications on faulty driver behaviour. Moreover, only a restricted number of vehicle factors were investigated (predominantly vehicle age and size), with only one study found exploring the contribution of vehicle defects and maintenance to safety. Regarding bus age, Rahman et al. (2011) found that older buses were more likely to be involved in injury crashes among bus–vehicle collisions on highways and drivers were found to have a higher probability of being at-fault when operating a bus of over 25 years old (Goh, Currie, Sarvi, & Logan, 2014a). In terms of bus size, Goh et al. (2014a) found that drivers operating shorter buses (12 m or less) were associated with a lower likelihood of being at-fault compared with those operating a longer bus. Similarly, Huting, Reid, Nwoke, Bacarella, and Ky (2016) identified that drivers driving an articulated bus were associated with a higher risk of crashes. According to Feng, Li, Ci, and Zhang (2016), buses with over 16 seats were more likely to be involved in higher severity crashes compared with buses with 9–16 seats. With regard to vehicle defects and maintenance, Mir, Razzak, and Ahmad (2013) conducted a survey among bus drivers and identified poor vehicle maintenance in addition to behavioural factors (including alcohol use and lack of seat belt use) as factors associated with crash occurrence. However, poor vehicle maintenance was based on drivers' experience and perception instead of objective tests or measurements, which lacked rigour.

Table 2.1 Risk factors of bus safety

	Driver					Environment			Vehicle		City/Country
Author	Age & experience	Gender	Work structure	Sleepiness & fatigue	Compliance & behaviour	Road	Time	Weather	Age	Size	
Blower and Green (2010)					✓						The US
Rahman, Kattan, and Tay (2011)	✓	✓		✓	✓	✓		✓	✓		Alberta, Canada
Kaplan and Prato (2012)	✓	✓			✓	✓					The US
Prato and Kaplan (2013)					✓	✓	✓				Denmark
Goh et al. (2014a)	✓	✓			✓	✓			✓	✓	Melbourne, Australia
Chu (2014)	✓			✓	✓	✓	✓				Taiwan
Feng et al. (2016)	✓	✓		✓	✓	✓	✓			✓	The US
Huting et al. (2016)	✓	✓	✓	✓		✓				✓	The US
Dorn and Wåhlberg (2008)	✓										The UK
Evans and Courtney (1985)	✓			✓			✓				Hong Kong
Pokorny, Blom, and Van Leeuwen (1987)			✓								Netherlands
Hamed, Jaradat, and Easa (1998)	✓				✓						Jordan
Chien-Ming (2012)	✓										Taiwan
Salminen, Vartia, and Giorgiani (2009)	Immigrant vs Native										Finland
(af Wåhlberg, 2004, 2007, 2008b)					✓						Uppsala, Sweden

	Driver					Environment			Vehicle		City/Country
Author	Age & experience	Gender	Work structure	Sleepiness & fatigue	Compliance & behaviour	Road	Time	Weather	Age	Size	
af Wåhlberg (2009)			✓								Uppsala, Sweden
af Wåhlberg and Dorn (2009)					✓						Britain/Sweden
Vennelle, Engleman, and Douglas (2010)				✓							Edinburgh, the UK
Razmpa, Niat, and Saedi (2011)				✓							Tehran, Iran
Cafiso, Di Graziano, and Pappalardo (2013)				✓							Italy
Anund, Ihlstrom, Fors, Kecklund, and Filtness (2016)				✓							Sweden
Santos and Lu (2016)				✓	✓						Manila, the Philippines
Wang (2011)					✓						Wuhan, China
Petzaell, Albertsson, Falkmer, and Bjoernstig (2005)								✓			Sweden
Hildebrand and Rose (2002)						✓					Australia, the US & Canada
Ziari and Khabiri (2006)							✓	✓			Tehran, Iran
af Wåhlberg (2008a)								✓			Uppsala, Sweden
Barua and Tay (2010)						✓	✓				Bangladesh
Evgenikos et al. (2016)						✓	✓				EU
La et al. (2017)					✓	✓					Hanoi, Vietnam
Mir et al. (2013)				✓	✓				Maintenance		Pakistán

Note: Author's synthesis of existing knowledge on risk factors examined in bus safety studies

2.3.3 Operational factors influencing safety performance

Buses, unlike private vehicles, are generally operated in a fleet setting. The literature has witnessed some interest in examining the relationship between fleet safety performance and organizational characteristics. However, it is noted that the majority of studies either did not differentiate bus from truck or only focused on the truck section, with little attention dedicated to the bus division.

Company size has received the most attention in the literature, with varied definitions for both size and safety performance, and the findings of the effect of this factor on safety performance are mixed. Generally, the literature suggests that companies with more capital (Chang & Yeh, 2005), higher total annual miles (Moses & Savage, 1994), and larger number of vehicles (Cantor, Corsi, Grimm, & Singh, 2016) (more than 10 vehicles in Cheung and Braver (2012) and Monaco and Redmon (2012)) were associated with lower crash rates (on an annual crashes per vehicle-mile basis). Chen (2008) identified similar findings that small companies (defined by the number of vehicles) were less likely to achieve satisfactory safety ratings than larger ones. On the other hand, Hwang, Boyle, and Banerjee (2019) identified no direct relationship between fleet size (defined by the number of vehicles) and safety ratings, while Mooren et al. (2014) compared the safety performance (indexed by the number of safety-related insurance claims per truck) of a sample of higher claiming, large companies (with >14 trucks) and found that companies with larger fleets had a higher mean claim rate than companies with smaller fleets. According to Cantor et al. (2016), the impact of company size on safety performance varied across industry segments.

Regarding operation classification (for hire vs private), there have been contradicting results on its influence. Corsi, Grimm, Cantor, and Sienicki (2012) and Moses and Savage (1994) found that for-hire carriers had significantly poorer safety performance than private carriers, while Chen (2008) stated that for-hire companies were more likely to receive satisfactory safety ratings than private ones.

In terms of years of experience, according to Moses and Savage (1994), the age of a trucking company did not influence its crash rates. Chang and Yeh (2005) reported similar findings that the experience of existing bus companies in local bus operation did not necessarily give them an advantage in the operation of intercity bus service. On the contrary, Cheung and Braver (2012) found that coach carriers with fewer years of business experience were associated with higher crash rates. Similarly, Cantor, Corsi, and Grimm (2017) found that more experienced carriers have significantly better safety performance in comparison to new entrant carriers.

Additional factors include financial status, journey distance, and traffic violations. Beard (1992) investigated the empirical relationships between safety performance (results of random roadside safety inspections) and financial condition (cash flow) of a group of coach carriers and found that the financial status is an important predictor of the fleet safety performance. The effect of journey distance has been examined in terms of its impact on driver fatigue (Friswell & Williamson, 2013) as well as the implications of travelling environment (urban or non-urban) (Moses & Savage, 1994), both of which have been shown to impact fleet safety. The number of traffic violations was found to be associated with safety performance (Chang & Yeh, 2005) and safety rating (Hwang et al., 2019), however, the relationship identified was not as straightforward. Other factors of specific interest to certain studies include union membership (Corsi et al., 2012), deregulation, fleet age (proportion of vehicles less than 5 years old), and mechanical failure rate (Chang & Yeh, 2005).

To summarise, there have been mixed findings regarding the impacts of operational characteristics on fleet safety performance. While much of the literature has focused on freight carriers and less so on bus operators, it is noted that there are substantial differences between buses and trucks (e.g. mass, operating characteristics), which influence safety performance. Passenger carriers were found to have significantly better safety performance or rating than the other carrier segments, with the relationships with safety rating identified for passenger and other carrier segments being different (Corsi et al., 2012; Hwang et al., 2019; Vulcan, 1987). Therefore, the knowledge in freight cannot be directly transferred to passenger carriers, leaving a gap in the literature with regard to the safety performance of bus operators.

2.4 Roadworthiness and Bus Maintenance Management

Both the reliability and safety of a bus service call for the operation of mechanically sound vehicles free of defects. Vehicles satisfying this requirement at any particular time are regarded as roadworthy (Rechnitzer et al., 2000). Most countries have implemented legislation requiring buses to stay roadworthy while in service. For example, in the UK, it is legislated that operators ensure that vehicles used on the road (both within and outside the UK) are roadworthy (Driver & Vehicle Standards Agency, 2018). In Victoria, Australia, too, bus operators need to ensure that their buses are roadworthy whenever they are carrying passengers (Bus Safety Victoria, 2017b). The regulations are regularly enforced, and the public transport safety regulator in Victoria (Transport Safety Victoria) oversees roadworthiness and has suspended several bus operators in the past few years for operating unroadworthy buses (Bus Safety Victoria, 2017a, 2018b, 2020).

Maintenance Management Systems (MMS) are intended to facilitate operators in maintaining vehicles in a roadworthy condition, which, therefore, has profound impacts on the reliability and safety performance of the bus service. An effective MMS helps schedule and monitor periodic inspections, maintenance, service, replacements, repairs, etc., facilitate the collection and management of data relevant to these activities (e.g. date, odometer reading, items inspected, personnel), keep track of the status of the fleet (e.g. defects, mechanical failures and worn parts reported during pre-trip inspection or operation), and flag issues for rectification or replacement before they deteriorate and lead to out-of-service conditions, breakdowns or contribute to a crash, thus safeguarding the roadworthiness, reliability, and safety of bus service (Dolce, 2009; Driver & Vehicle Standards Agency, 2018). Proper vehicle maintenance was considered as the foundation of service reliability (Guenthner & Sinha, 1983; Nallusamy et al., 2015) and was associated with a reduction in defect-related crashes (McDole, 1975) and a lower likelihood of being involved in a road crash (Blower et al., 2010).

2.4.1 Overview of bus maintenance management

Despite the recognition of the benefits of maintaining the roadworthy condition of bus fleets and the positive impacts of implementing MMSs, no published literature was identified that addresses the origin or the development of bus maintenance management structure. In the absence of the literature, this section reviews the literature on fleet MMS by benchmarking the regimes and describing practices in peer jurisdictions.

Summarising the practices from both domestic (Victoria, New South Wales, Australia) and international (Britain, Canada) jurisdictions, there are typically two levels of bus inspections in the MMS, which differ in scope and depth (Bus & Coach Association NSW, 2011; Bus Safety Victoria, 2017b; Canadian Council of Motor Transport Administrators, 2014; Driver & Vehicle Standards Agency, 2018). They can be categorized broadly as pre-trip inspections and time-distance based inspections.

The pre-trip inspection, described as a 'daily trip inspection', 'daily walkaround check' or 'circle check' in some jurisdictions, is a general sight and sound check of the accessible components of a vehicle (usually without the use of dedicated facilities or equipment). It is intended to detect gross defects and flag issues at an early stage to prevent them from developing into serious mechanical failures. Inspections are usually undertaken by the driver or other personnel deemed adequate by the operator prior to the first passenger-carrying trip of each operating day. A checklist approved by the operator is followed and the results are recorded accordingly. If significant defects or signs of potential defects that could adversely affect the reliable or safe operation of the bus are identified, the bus is prevented from entering service; hence, it can be regarded as a simple roadworthiness check (Bus & Coach Association NSW, 2011; Bus Safety Victoria, 2017b; Canadian Council of Motor Transport Administrators, 2014; Driver & Vehicle Standards Agency, 2018).

The time-distance based inspection, also known as a safety, routine, regular or periodic inspection in some jurisdictions, comprises preventative maintenance and repair of excessively worn or failed vehicle components (e.g. correcting potential structural and operational failures, major rebuilds, collision repair, other bodywork) (McDole, 1975). The schedule is usually specified as a combination of elapsed time and/or travel distance, depending on known failure patterns of individual components or systems. The scheme is usually set out by individual operators and based on manufacturer's recommendations, government safety regulations, and operator expertise and experience. Inspections and the consequent maintenance can be conducted either by internal staff or external contractors.

In recent years, computerized MMSs, a systematic and automated (e.g. send reminders when they are due) approach to managing inspections and maintenance, have been gaining popularity among operators (Haghani & Shafahi, 2002). In the FMCSA/UM Survey of Safest Motor Carriers, 56 percent of respondents reported using a computerized system (Corsi & Barnard, 2002). As opposed to a manual system, the electronic one helps safeguard the fleet from human errors. According to field evidence, organizations using computerized MMS reported higher compliance with vehicle maintenance and greater rates of servicing documentation than organizations with no such system in place.

To summarise, each type of inspection practice has a unique purpose. A pre-trip inspection is essentially a high-level function check, while a time-distance based inspection is more focused on maintenance, service, and repair. They complement each other to ensure the roadworthiness of vehicles.

2.4.2 Components of bus MMS

2.4.2.1 Planning & scheduling

An important feature of effective MMS is to ensure there is a system to plan and schedule maintenance, and a substantial body of research has been devoted to devising innovative approaches to address various aspects associated with fleet maintenance scheduling and planning. In terms of budget and funding, Mishra, Sharma, Khasnabis, and Mathew (2013) developed an optimization model to allocate funds of budget constraints among purchasing, operating and maintaining a transit fleet to maintain service standards. Regarding the delicate balance between preventative and reactive maintenance (breakdown repair), Bakr and Kretschmer (1977) proposed an approach towards the determination of bus maintenance schedules with the purpose of striking the balance between bus fleet maintenance cost and reliability performance. It features a cost function that takes into account the sum of the cost of periodical preventive maintenance and the cost of failures and unscheduled repairs. Similarly, Zhou, Fox, Lee, and Nee (2004) proposed a multi-agent system (MAS) to solve the bus maintenance scheduling problem comprising two sub-problems, predictive and reactive scheduling, which is distributed and dynamic in nature. In terms of optimizing the maintenance workload and resources (facility, staff and time allocation), Haghani and Shafahi (2002) presented a mathematical programming approach to scheduling maintenance activities in a bus transit system. It takes as input a given daily operating schedule for all buses assigned to a depot along with available maintenance resources and attempts to design daily inspection and maintenance schedules for the buses that are due for inspection to minimize the interruptions in the daily bus operating schedule and maximize the utilization of the maintenance facilities. Centeno, Chaudhary, and Lopez (2005) presented a systematic method for determining maintenance and repair time standards for transit vehicles, which incorporates relevant factors such as maintenance procedures and work bay components and design to assist supervisors during complex management decisions for resource allocation and scheduling. Adonyi, Heckl, and Olti (2013) applied the P-graph (process graph) framework which considers not only the night period but the whole day including the usually unused time of the buses during daytime to schedule bus maintenance activities.

Summarising the above, maintenance planning and scheduling is a task closely tied with resource allocation and management.

2.4.2.2 Factors influencing maintenance practices

Inspection and maintenance practices vary across fleets, and the fleet characteristics commonly observed in the literature to have impacts on maintenance practices are operator size, location, and service type.

Regarding operator size, there are numerous differences between larger and smaller operators, including the size of the maintenance facilities (with larger operators having larger facilities compared with smaller operators) (Tomeh et al., 2001), and differences between undertaking maintenance in-house or contracting others to undertake maintenance. In general, larger operators tend to perform most maintenance activities in-house while small operators are more inclined to outsource, and this is mostly due to the costs, resources, and expertise requirement imposed by in-house maintenance (Corsi & Barnard, 2002; Driver & Vehicle Standards Agency, 2018). Sustaining an internal maintenance team and the necessary equipment can be costly for small operators, so outsourcing is often preferred amongst this group as the fees are comparatively low. The high variability in inspection and maintenance quality can, however, be of concern (Izquierdo, Sesemann, & Alonso, 2009). The adoption of computerized fleet MMSs also varies sharply by fleet size (78 percent for large fleets versus 23 percent for small ones), according to Corsi and Barnard (2002).

A number of studies suggest that operator location influences inspection and maintenance practices. Ng et al (2012) noted that rural operators usually run longer routes on poorer road conditions which result in accelerated rates of component wear induced by both rough and unsealed road surfaces as well as potentially higher travel speeds on such roads, therefore requiring more frequent and intensive inspections compared with their urban counterparts. Peck et al. (2015) found a similar outcome with private vehicles, suggesting that the more rural/remote the registration zip code of the vehicles, the more maintenance was required. Field evidence confirmed that the frequency that buses travel on unsealed roads has a substantial impact on maintenance workloads.

With regard to service type, the operating characteristics are significantly different among school, transit, intercity, and other buses (Rahman et al., 2011). For instance, transit buses run on urban streets with frequent stops, while intercity buses operate mainly on highways and rural roads with fewer stops. These differences in operating characteristics result in distinct patterns of wear, which leads to varying inspection practices. Tomeh et al. (2001) provided evidence that inspection standards vary across service types and express service vehicles were found to be maintained to a higher standard in all major components, compared with vehicles used for standard fixed-route service.

2.4.2.3 Indicators for maintenance performance

In accordance with the aim of ensuring the reliable and safe operation of the fleet, maintenance performance is often evaluated by indicators aligned with mechanical failures. Maze and Cook (1987) conducted a survey among maintenance managers and identified miles per road call (equivalent to the more commonly known Mean Distance Between Failure (MDBF)) and road calls per bus per month as the most widely recognized indicators for maintenance performance. Similarly, miles per road call (MDBF) was recognized as a popular indicator for vehicle maintenance performance among the maintenance managers (List & Lowen, 1987). Chang and Yeh (2005) used the number of mechanical failures during operation per million of kilometres travelled in one year to represent the quality of a bus company's vehicle maintenance. Other common indicators include mean time between failures and mean vehicle downtime (Cohen & Silkunas, 2018). Some issues are noted with the use of these performance indicators. The data needed to calculate them usually come from internal records, which may not be properly or systematically recorded (especially in small operations) or easily accessible. More importantly, it can be problematic to compare mechanical-failure based indicators between operators as the standards for what constitutes or recorded as a "failure" may vary (Cohen & Silkunas, 2018).

2.4.3 Legislated mandatory, independent inspections

2.4.3.1 Description

In addition to the two internal inspections illustrated above that are implemented at the discretion of individual operators, most countries (especially high- and middle-income countries) and jurisdictions require and mandate an external periodic safety inspection for commercial buses (e.g. the United States, Canada, the European Union, Britain, Australia, Malaysia, China).

The mandatory, independent inspection, referred to as a Periodic Motor Vehicle Inspection (PMVI) or annual inspection in some jurisdictions, is a comprehensive examination of the bus undertaken by an independent, government-authorized tester at fixed intervals to verify vehicle roadworthy compliance (Bus Safety Victoria, 2018a; Canadian Council of Motor Transport Administrators, 2014; Driver & Vehicle Standards Agency, 2018; Queensland Government, 2018). It is therefore also referred to as the roadworthiness test (the four terms, mandatory, independent inspections, PMVI, annual inspections, and roadworthiness tests are terms used in different jurisdictions and will be used interchangeably in the thesis). The bus systems and components that are inspected fall within the following categories: Engine & Driveline, Steering & Suspension, Brake System, Body & Chassis, Wheels & Tyres, Seats & Seatbelts, Lamps, Signals & Reflectors, Electrical System, Windows & Windscreens, Windscreen Wipers & Washers, and Other Items (Canadian Council of Motor Transport Administrators, 2014; National Heavy Vehicle Regulator, 2016). The frequency of this inspection type is usually biannual or annual, depending on the jurisdiction (e.g., biannual in Canada, New South Wales, and Queensland, Australia while annual in Britain, South Australia, and Victoria, Australia). Buses deemed roadworthy (Driver & Vehicle Standards Agency, 2018), meeting minimum vehicle safety standards (Queensland Government, 2018), in a safe condition (Canadian Council of Motor Transport Administrators, 2014); safe for normal road use (Bus Safety Victoria, 2018a) are issued with a roadworthy certificate covering the period until the next scheduled check. The requirements for roadworthiness have clear implications on vehicle safety. If key components have worn, deteriorated, or are identified as being defective, the bus is deemed to have failed and a test report listing the defective areas is issued to the operator. Some jurisdictions require a re-inspection of buses that fail the inspection (Canadian Council of Motor Transport Administrators, 2014; Queensland Government, 2018) while others do not (Bus Safety Victoria, 2018a). However, in other jurisdictions, such as Victoria, operators are required to keep records of the defects detected, rectify them before putting the bus back into service and retain evidence of rectification which must be presented in the event of an audit by the public transport safety regulator (Bus Safety Victoria, 2017b).

2.4.3.2 Mandatory, independent inspection data

The mandatory independent inspection can be seen as an audit or compliance check of the inspection and maintenance practices implemented by commercial vehicle operators (Canadian Council of Motor Transport Administrators, 2014). It is recognized as having the potential to identify operations with inadequate maintenance practices and improving the efficacy of regulation (McDole, 1975). The safety regulator in Victoria, for instance, uses the annual inspection results and identifies "operators with buses that fail in identical components in two consecutive annual safety inspections" as the guideline for the selection of operators for auditing. Peck et al. (2015) demonstrated the value of PMVI data in providing various data-driven recommendations to inform policy questions pertaining to vehicle safety.

Compared with the indicators of maintenance performance illustrated in Section 2.4.2.3, which are failure-oriented and have limitations of data availability and varied standards of failure definition across operators, the PMVI data has noteworthy merits. PMVI is mandatory for buses, indicating extensive coverage of the vehicle population in the jurisdiction. It has been steadily implemented for decades in a number of countries and jurisdictions and generates continuous records. PMVI is external, conducted by independent licensed testers, ensuring that the results are objective, and implies a certain degree of uniformity. In view of the above, it makes a promising alternative to the indicators in evaluating fleet maintenance performance and could be made better use of.

2.4.3.3 Effect of mandatory, independent inspections

Notwithstanding the evidence that PMVI is mandatory for heavy commercial vehicles including buses in most jurisdictions, there is a low motive or research interest for examining the rationale of its implementation and consequently little empirical research interest into its effect on heavy vehicles. The only relevant article that was identified at the time of writing is authored by Assemi and Hickman (2018), which investigated the effectiveness of periodic heavy vehicle inspections by examining their impact on the factors contributing to the incidence and severity of heavy vehicle crashes. The main findings highlighted the important role of periodic inspection habits in the future likelihood of crashes and provided empirical support for updating and enforcing the existing policies of heavy vehicle inspections to improve road safety outcomes.

PMVI policy for private vehicles, on the other hand, varies across jurisdictions. Driven by political (Sutter & Poitras, 2002) and regulatory motives, a substantial amount of research has examined the economic (Little, 1968; Loeb, 1985; Moghadam & Livernois, 2010) and safety implications (relating to the reduction of defects and crashes) of PMVI on private vehicles, based on which the argument of the 'adoption versus abortion' is anchored. The following sections draw on the literature on private vehicles for the discussion.

2.4.3.3.1 PMVI on vehicle condition (private vehicles)

The effects of PMVI on reducing defects in the private vehicle fleet have been examined extensively using a variety of methods (time-series, cross-sectional and case-control analysis) and it is generally agreed that PMVI is effective in reducing the incidence of technical defects and improving the mechanical condition of private vehicles (Christensen & Elvik, 2007; Keall & Newstead, 2013; Peck et al., 2015; Rechnitzer et al., 2000).

McCutcheon (1968) compared the mechanical condition of private vehicles in jurisdictions where vehicle inspections are required annually, biannually, triennially, and never. The results showed that vehicle populations subject to periodic inspections were in substantially better mechanical condition than populations not and the more frequent the inspections were, the better the mechanical condition. According to National Highway Traffic Safety Administration (1989), PMVI was effective in eliminating the number of poorly maintained vehicles on the road. Fosser (1992) compared the number of defects of vehicles which were randomly assigned to three different experimental conditions (inspected every year, every third year and never) in the same jurisdiction and the vehicles subject to periodic inspection were found to be in slightly better technical condition compared with those that were never inspected. Christensen and Elvik (2007) compared the mechanical condition before and after the introduction of PMVI and found that PMVI strongly reduced the number of technical defects in private vehicles (excluding trucks and buses) in Norway.

More recently, Keall and Newstead (2013) demonstrated that reducing the inspection interval from 12 months to 6 months decreases the prevalence of safety-related defects by 13.5 percent (95% confidence interval: 12.8–14.2%) in New Zealand. Peck et al. (2015) examined the effect of PMVI in reducing vehicle defects and found reductions in the proportion of defective vehicles from 12-18 percent without PMVI to two percent with PMVI.

2.4.3.3.2 PMVI on safety performance (private vehicles)

In contrast to the evidence demonstrating overall benefits for mandating regular and frequent PMVI (at least annually) to improve vehicle condition, the evidence surrounding the effectiveness of inspection programs on reducing crashes is less clear and inconclusive.

Cross-sectional analysis

Robinson (1989) conducted a multivariate study to estimate the effect of PMVI on US fatality rates. All fifty states were included with 29 having PMVI, nine having a system of random inspections, and 12 states with neither. Differences in driver behaviour, traffic regulations, and vehicle characteristics were controlled for, however, no effect of PMVI on the fatality rate was detected. The authors acknowledged that, despite the attempts to include as many variables as possible, there were numerous limitations including potential omitted variable bias and small sample size (n=50), making it difficult to draw conclusions based on statistically significant findings.

Das, Geedipally, Dixon, Sun, and Ma (2019) investigated the effect of state-mandated vehicle inspections in the US using the Fatality Analysis Reporting System (FARS; the national census of all traffic crashes resulting in fatalities) and the Vehicle Complaints Database (records of public complaints about vehicles and transport-related equipment component failure information). The authors compared monthly complaints and fatal crashes in States with and without inspections. Applying “Cohen’s d” statistic, the results indicated that states with inspections anticipate a smaller number of monthly safety-related vehicle defect complaints from owners and fatal crashes with safety-related defect complaint records, compared with the states without inspection, suggesting that mandatory PMVI may have a positive effect on safety.

Several concerns about using cross-sectional regression techniques to examine the effect of PMVI on crash rates have been noted in the literature. PMVI programs are heterogeneous, with considerable variation in the items inspected, procedures, equipment, inspection criteria, and rules and regulations between jurisdictions. In addition, road safety conditions across jurisdictions are not homogeneous. States with compulsory inspections generally have a strong overall desire to reduce traffic crash rates and are likely to have a variety of other road safety programs in place with likely greater impacts on crash rates than inspection schemes alone (Fosser, 1992). Despite the efforts to include as many relevant factors as possible, it is impossible to acquire exhaustive data on these variables and regression models cannot fully account for the differences between the jurisdictions being compared. All of the above can compromise the accuracy of the estimates.

Time series analysis

Using data from 1998 to 2002 in Norway, Christensen and Elvik (2007) conducted a study comparing crash rates before and after the implementation of an inspection program to estimate the effect of PMVI on crashes. Negative binomial regression was applied to model the number of crashes as the outcome variable, while statistically controlling for the effects of the following confounding factors: year of inspection, car age, mandatory insurance coverage, and collision insurance coverage. No evidence of any effect of periodic inspections on crash rates was identified.

Hoagland and Woolley (2018) utilized a synthetic controls approach and reached a similar conclusion that ending PMVI did not result in a significant increase in the frequency or intensity of crashes attributable to mechanical failure.

A concern about using time-series analyses to investigate crash rates is that multiple factors are expected to manipulate crash rates during the study period. For example, roads become safer, cars become safer, and traffic management is improved.

Case-control analysis

Fosser (1992) designed a case-control study to evaluate the safety effects of PMVI in Norway, comparing the effects of annual inspection and inspection every third year to a control condition of 'no inspection'. A total of 204,000 private vehicles were randomly assigned to three different experimental conditions groupings: 46,000 vehicles that were inspected annually over three years; 46,000 vehicles that were inspected once during the three years; and, 112,000 vehicles that were not inspected. No differences in crash rates were found among the groups and the authors concluded that neither of the two inspection frequencies had any effect on crash rates. The experiment was conducted in Norway where there was a high level of random roadside inspection (about 20% of vehicles per year), which might have been a sufficient incentive on its own for owners to maintain their vehicles, impairing the power of the study.

Blows, Ivers, Connor, Ameratunga, and Norton (2003) conducted a case-control study in Auckland, New Zealand, comparing the risk of injury crash between the following groups: (1) vehicles that had a safety inspection within the past six months (case group) and those that had not (control group) and; (2) vehicles that had their tyre pressures checked within the past three months (case group) and those that had not (control group). Logistic regression modeling was introduced to control for a range of confounding factors including driver age, sex, marijuana use, ethnicity, self-reported speed, hours per week of driving exposure, and license type. It was estimated that vehicles that had not undergone a safety inspection within the previous six months were three times more likely to be involved in an injury crash. Vehicles that had not had their tyre pressures checked within the previous three months also had significantly greater odds of being involved in an injury crash. Consequently, it was concluded that six-month vehicle inspections and three-monthly tyre pressure checks were both associated with a reduced risk of an injury crash.

The case-control analysis does not suffer the challenges of segregating the effects of PMVI due to the intervention of confounding factors, as is faced by time-series and cross-sectional analysis. However, caution should be exercised against potential selection bias when sampling case and control groups.

2.4.4 Random roadside inspections

Apart from PMVI, the random roadside inspection is an unannounced spot check administered by the safety regulators to monitor the roadworthy condition of in-service vehicles to ensure compliance with the regulations. This practice is widely enforced in jurisdictions (Bus Safety Victoria, 2014; Canadian Council of Motor Transport Administrators, 2014; Driver & Vehicle Standards Agency, 2018). There has been research interest in the selection of vehicles for roadside inspections based on historical data (Lantz, 2000; Lantz, Blevins, & Hillegass, 1997).

2.5 Summary, Research Gaps, and Opportunities

Fleet maintenance performance has been recognized as playing an essential role in ensuring the roadworthy, reliability, and safety performance of bus services, which have been found to have wider impacts on both the provider and user of bus service. A comprehensive understanding of fleet maintenance performance is the basis for effectively identifying fleets with inadequate maintenance practices, identifying the factors that facilitate or hinder good maintenance performance, and implementing regulatory practices to improve the roadworthy performance of fleets. However, an examination of the literature suggested there is currently very limited research in understanding or evaluating the maintenance and roadworthy performance of bus fleets. Existing research has been preliminary, scattered, on a limited scale, or of poor data accessibility and quality, therefore lacking rigour and precision. This warrants further research. Mandatory independent inspection data has shown great potential in assessing vehicle maintenance performance while being free from the limitations of existing indicators. Notwithstanding, this data source is yet to be utilized in the current literature.

Of additional interest is the identification of the road safety impacts of bus roadworthy performance. While vehicle defects have been identified as contributing to bus crashes, the effect of vehicle defects—and roadworthiness in general—on bus safety has received very little research attention compared to other risk factors such as driver characteristics. Moreover, bus safety performance is rarely studied at the fleet level, in contrast to the literature on freight carriers, which has returned inconclusive findings about the effects of operational characteristics on safety performance.

In view of the above, a number of knowledge gaps and opportunities for further research have been identified and grouped as follows: bus maintenance, roadworthy, and safety performance (summarized in Table 2.2). These findings have guided the development of the overall aims and research questions of the current research program, which aims to provide an in-depth understanding of the aspects surrounding bus maintenance, roadworthy, and safety outcomes.

The following chapter presents an outline of the overall research framework, approach, and details of data used in this research.

Table 2.2 Existing knowledge gaps that provide further research opportunities

Area	Knowledge gaps	Research Opportunities
Bus maintenance and roadworthy performance	Existing studies have generally fallen short of adequately assessing fleet maintenance performance.	Evaluating maintenance performance using roadworthiness test results
	The potential of the widely-collected mandatory independent inspection data in evaluating fleet maintenance performance has been overlooked.	
Bus roadworthy and safety performance	The impact of bus roadworthy performance on safety outcomes had rarely been examined, especially not in relation to other risk factors.	Examining the effect of bus roadworthiness in relation to other key risk factors on safety performance.
	The safety performance of buses is rarely studied at the fleet level, as opposed to the truck sector.	

Chapter 3 RESEARCH FRAMEWORK, METHODOLOGY, AND DATA

3.1 Introduction

This chapter provides an overview of the theoretical framework and methodological approach guiding this research. First, the research aims and objectives are described, followed by a presentation of the theoretical framework. The overall research framework adopted to guide research efforts to achieve the research objectives is then illustrated. The data sources are then presented and their integration illustrated. Finally, this chapter concludes with a summary.

3.2 Research Aims and Objectives

This research aims to provide an in-depth understanding of the factors influencing bus fleet maintenance, roadworthy, and safety performance in Victoria, Australia. Following the research aim, four specific research objectives were formulated.

1. To establish a comprehensive understanding of Victorian bus inspection outcomes
2. To evaluate current inspection and maintenance practices of Australian bus operators
3. To identify the contributing factors to bus inspection outcomes and quantify their effects
4. To explore the effects of bus fleet roadworthy outcomes in relation to other operational characteristics on fleet safety performance

The specific research questions are:

1. What are the inspection and maintenance practices among operators with different characteristics (e.g. size, location, and service type)?
2. How do operators with different characteristics (e.g. size, location, and service type) perceive bus inspections and how do these perceptions relate to inspection practices?
3. What are the distinct patterns of bus inspection outcomes and what are their characteristics?

4. What is the relative performance with regard to inspection outcomes among bus operators?

5. What are the factors that contribute to bus annual inspection outcomes and how do these factors impact roadworthiness outcomes?

6. How does fleet inspection outcome performance relate to safety outcomes and what are the additional contributing factors?

3.3 Theoretical Framework

This thesis refers to the Safe System as the primary theoretical framework, which provides scientific justification for studying vehicle safety.

The Safe System approach forms the basis for the UN Decade of Action for Road Safety and has been widely adopted as the framework of the road safety strategies both in Australia (National Road Safety Strategy, 2016) and internationally (Chen & Meuleners, 2011). It is based on an ethical position where it can never be acceptable that people are killed or seriously injured on the road (PIARC, 2003) and Australia's Safe System aspires to eventually eliminate fatalities and serious injuries within the road transport system (Corben, Logan, Fanciulli, Farley, & Cameron, 2010).

The Safe System not only recognizes the roles of the driver, vehicle and road environment in contributing to crashes but acknowledges that road safety depends on the management of the interactions among infrastructure safety features, vehicle safety features, travel speeds of vehicles and road users (Figure 3.1) (Corben et al., 2010; National Road Safety Strategy, 2016; PIARC, 2003). It also explicitly recognizes human errors and the physical frailty of humans (Corben et al., 2010), and aims to develop and design a 'forgiving' road transport system that is able to accommodate these limitations (National Road Safety Strategy, 2016; PIARC, 2003).

The Australian National Road Safety Strategy (2016) interpretation of the Safe System in the following aspects is particularly relevant to the context of this research, with the contributions of vehicle safety being acknowledged.

Safe vehicles acts as one of the four key elements in the Safe System, which emphasizes the benefits and opportunities from continually improving vehicle safety, including encouraging design standards that enhance the capacity of vehicles to prevent crashes and protect road users in the event of a crash, encouraging corporate fleet operators to purchase vehicles with high safety ratings (for example, requiring 5-star Australasian New Car Assessment Program rated vehicles where possible and ensuring key safety features are fitted to all new vehicles) and promoting the adoption of operating principles to ensure all vehicles meet roadworthy standards and are fit for use on the roads (National Road Safety Strategy, 2016; PIARC, 2003).

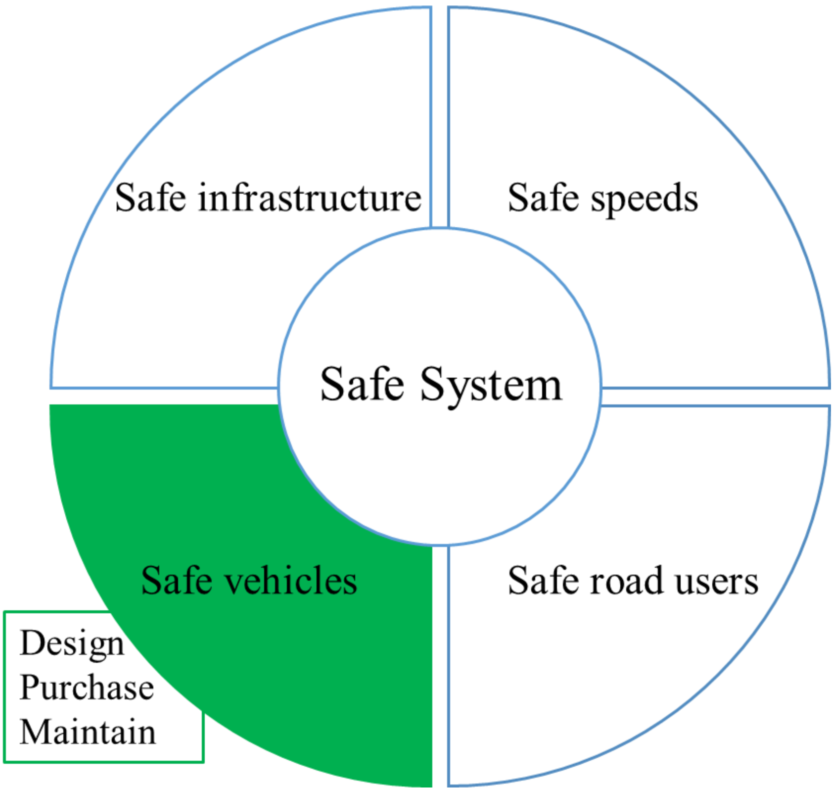

Figure 3.1 The Safe System

Note: Safe system diagram adapted from PIARC (2003) and National Road Safety Strategy (2016)

3.4 Research Framework and Components

3.4.1 Research framework

The research framework (Figure 3.2) illustrates the interactions among the key elements of the study design to achieve the research objectives, as well as provide justification for the development (logic and progression) of the research objectives.

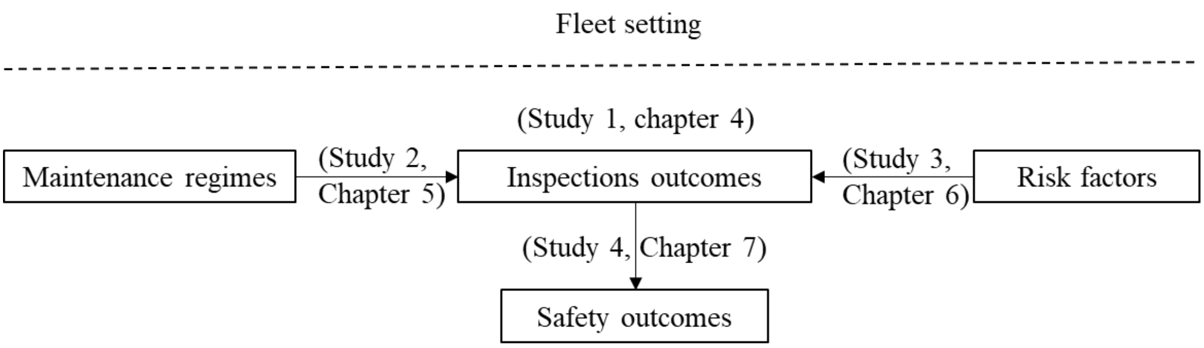

Figure 3.2 Research framework

It is important to reiterate, as noted in Section 2.3.3, that bus performance, unlike that of private vehicles, needs to be approached in the context of the fleet setting, and this is the overarching tone for this research.

In correspondence with the framework, four key research components were developed to guide efforts towards the research objectives. Each research component is the focus of a result chapter in Section II, with the relationships between each illustrated in Figure 3.2. The following sections provide a brief account of each of the four research components. Detailed descriptions of the research context, methodology, and key findings from each research component are presented in accordance with this framework in relevant chapters.

3.4.2 Research component 1

The first research component (Study 1, Chapter 4) focused on developing a structured approach to establishing a comprehensive understanding of the current bus inspection system and outcomes, at both individual and fleet level. As elaborated in Section 2.4.3.2, annual bus inspection outcomes are used as an appropriate and available proxy measure of bus roadworthy performance. The dataset used in this study was compiled via the procedure detailed in Section 3.5. The performance of the 14 main inspection components during annual bus inspections was examined and a multilevel latent class analysis was applied to synthesize failure patterns and their compositions among operators.

3.4.3 Research component 2

The second research component addressed the maintenance aspect and evaluated the current self-reported inspection practices of Australian bus operators. A questionnaire was developed to collect information on inspection practices, operational characteristics, and perceptions of inspections. The study was approved by Monash University Human Research Ethics Committee 'MUHREC' (reference number 2016-0210-1022). Professional bus associations in Victoria, Queensland, and South Australia, acting as industry representative bodies for accredited bus operators in those states, and Transport Safety Victoria (the government safety regulator of public transport in Victoria) assisted with distributing the questionnaire. A total of 171 valid responses from the three states made the sample. A series of statistical analyses were performed to identify the associations among inspection practices, operational characteristics, and perceptions of inspections. Further details on the design of the questionnaire, the method of data collection, and data analysis are presented in Chapter 5.

3.4.4 Research component 3

The third research component focused on identifying the factors associated with roadworthy performance. Similarly, the roadworthy performance was indicated by the annual inspection outcomes and data acquisition process illustrated in Section 3.5. A multilevel modeling approach was adopted to account for the hierarchical data structure, which enabled the quantification of effects attributable to inspections, vehicles, and operators, as well as the determination of the level of inspection failure risk associated with individual operators.

3.4.5 Research component 4

The fourth and final research component aimed to extend the understanding of the impact of fleet roadworthy performance, as measured by inspection outcomes, on fleet safety outcomes. It focused on modeling the incident outcomes to understand the impact of fleet roadworthy performance in relation to other key operational characteristics on fleet safety performance. The dataset used for this study was compiled via the procedure illustrated in Section 3.5. For analytical rigour, the data structure (disaggregate vs aggregate) was inspected, the derived methodological challenges (e.g. excess zeros) were examined, different count data models were explored, and a comparison of model performance was exercised to arrive at the most accurate estimation. The results were discussed and interpreted in the context of both existing literature and field experience.

3.5 Research Data

As discussed in Section 2.4.2.3, a key challenge that researchers face in investigating fleet maintenance, roadworthy, and safety performance is obtaining qualified data. Datasets for this research (two providing performance data and the others supplementing information) were procured under a confidentiality agreement with the corresponding agencies. The details are provided below.

3.5.1 Research Context - Accredited bus operators in Victoria

Under the Bus Safety Act 2009 (Victorian Legislation and Parlimentary Documents, 2009), an operator that intends to use buses with more than 12 seats to operate a commercial bus service needs to be accredited in order to provide any of the following services: route bus service, tour and charter bus service, demand responsive bus service, courtesy bus service (other than a non-commercial courtesy bus service) or local bus service. This research focused on buses managed by accredited operators in Victoria, which is equivalent to commercial bus operators in other jurisdictions.

3.5.2 Bus annual inspection dataset

Annual bus inspection records were progressively retrieved from TSV and data were acquired for a period of four years, from 1 Jul 2014 to 30 Jun 2018. The data comprised inspection details including inspection date, odometer reading, and inspection results (pass/fail on each of the 14 inspected components) and vehicular information including Vehicle Identification Number (VIN), Registration Number, vehicle make and year of manufacture. Between 4 and 8.5 percent of Victorian bus annual inspections during the study period were conducted up to four weeks later than scheduled. Consistency and accuracy checks were carried out on the dataset using vehicle odometer readings collected at sequential annual inspections.

3.5.3 Bus incident dataset

Similar to the annual inspection data, bus incident dataset for the same period was obtained from TSV, which managed the incidents that resulted in or had the potential to result in fatalities, injuries, property damage or loss of control of the bus, as reported by bus operators (Victorian Legislation and Parlimentary Documents, 2009). The data comprised incident details including incident date, time, description, and vehicle details including VIN and Registration Number.

3.5.4 VicRoads vehicle registration database

VicRoads is the road and traffic authority in the state of Victoria and is responsible for vehicle registration. The VicRoads vehicle registration database was sourced to resolve missing or conflicting information on vehicular characteristics in the inspection dataset, including identity, make, and year of manufacture.

3.5.5 Operator dataset

Australian Bus Fleet Lists[1] provides information on buses currently and previously utilized by operators around Australia and was sourced to supplement operator information (identity, depot address, service type), as well as vehicular characteristics including vehicle body and configuration. Road Safety Inspections (RSI), which conducts approximately 75 percent of Victorian bus inspections, was sourced to supplement the records unavailable in the Australian Bus Fleet Lists and cross-validate operator information (identity, especially in the case of change of ownership and depot address).

3.5.6 Data integration

The datasets above were integrated by matching VIN, the unique vehicle identification number assigned to each vehicle by NEVDIS[2] (National Exchange of Vehicle and Driver Information System). After a rigorous procedure of data validation and integration, resolving problems with missing or conflicting data, a unique dataset was compiled for this research, with the procedure illustrated in Figure 3.3. The final outcome was that 13 percent of the inspection records remained with missing or conflicting attributes and 6 percent were considered outliers. These two groups were excluded from further analysis. As a result, a total of 24,310 inspection records for 6,841 buses run by 234 Victorian operators made up the final sample.

The integration enabled the determination of fleet size, and operators were classified into ‘small’ (up to 25 buses), ‘medium’ (26-100 buses) and ‘large’ (more than 100 buses), the standard of which was set by the industry's general rule of thumb and literature (Lowe, 2016). Based on their depot address, each of the operators was assigned to one of the five classes of remoteness: Major Cities, Inner Regional, Outer Regional, Remote Australia and Very Remote Australia, as defined in the Accessibility and

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[1] http://www.busaustralia.com/fleetlists/index.php

[2] https://austroads.com.au/drivers-and-vehicles/nevdis

Remoteness Index of Australia, ARIA+ (Australian Bureau of Statistics, 2016). Operators were classified into the following categories based on their predominant service type: route, charter and tour, and school and other operators. Further details on the data structures and variables used for specific research components are provided in corresponding chapters.

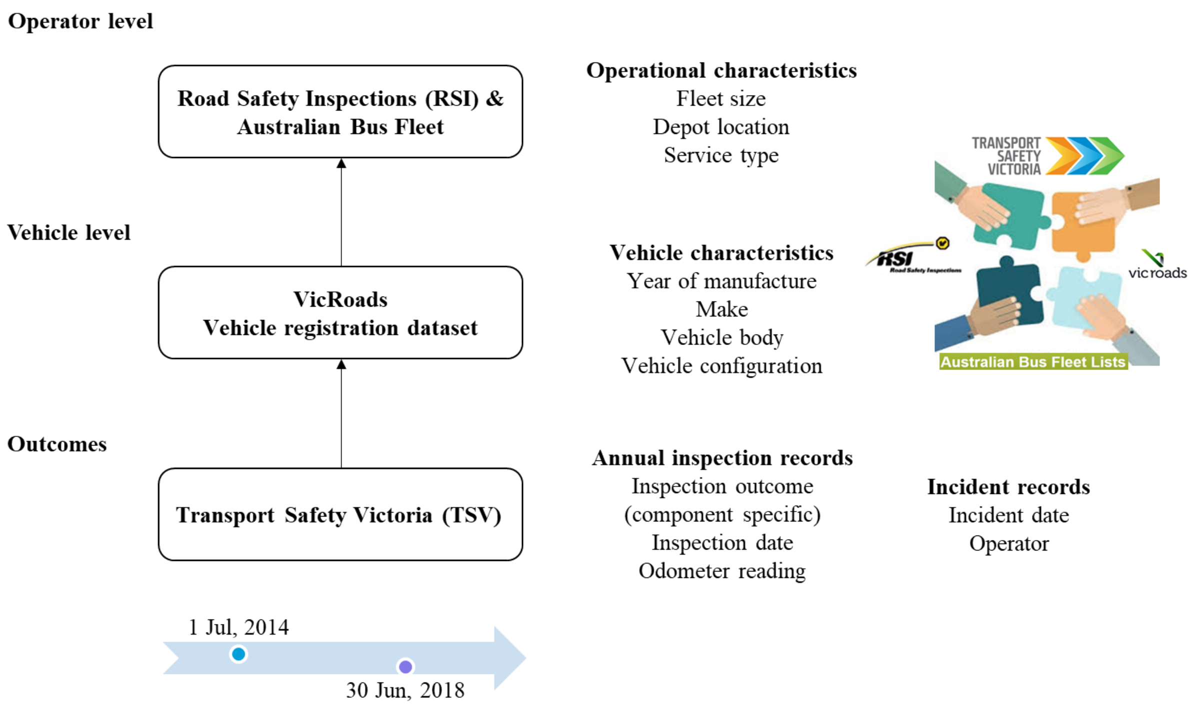

Figure 3.3 Illustration of data sources

3.6 Summary

In this chapter, the research objectives formulated to attain the research aim were presented, as well as the specific research questions. The overall research framework devised to oversee the implementation of a structured approach was illustrated. In doing so, four research components were articulated to guide research efforts to attain the objectives.

The first task focused on developing a structured approach to establish a comprehensive understanding of the current roadworthy condition (presented in Chapter 4). The next task tackled the maintenance aspect and evaluated the state-of-art inspection practices of Australian bus operators (presented in

Chapter 5). Following this, the risk factors of poor bus roadworthiness was investigated and quantified, including inspection, vehicle, and operator related factors (presented in Chapter 6). The final task explored the impact of fleet roadworthy performance in relation to other key risk factors on fleet incident outcomes (presented in Chapter 7). Robust methodological approaches available in current research practice were scrutinized for this research to accomplish the research tasks.

The data used in this research was gathered from four key sources: (1) TSV inspection and incident datasets; (2) VicRoads vehicle registration database (3) Australian Bus Fleet Lists and Road Safety Inspections (RSI) dataset, and (4) questionnaire on bus operators. Using a combination of data sources overcame the limitations associated with using a single one. The acquisition of data at different levels facilitated the realization of hierarchical data structure and fleet setting, and the consequent application of a multilevel modeling approach, which examined bus roadworthiness from different aspects and elevated the essence of the research.

The next chapters (4-7) present the detailed aims, data, methods, results, and key findings associated with the four research components formulated in this in this chapter.

Chapter 4 UNDERSTANDING BUS ROADWORTHINESS THROUGH ANALYSIS OF INSPECTION OUTCOMES

4.1 Introduction

This chapter aims to develop a structured approach to establish a comprehensive understanding of the inspection outcomes and the indicated roadworthy condition of buses, focusing on Victoria, Australia.

This chapter starts with an explorative analysis of the heterogeneity of inspection failures. It then ventures to extract meaningful subtypes of bus inspection outcomes, where the likelihood and magnitude of failures are synthesized. Using multilevel latent class analysis, operator types with different failure patterns are identified, and the characteristics of each described. It concludes with a discussion of the implications of inspection outcomes for bus safety regulation and future research directions.

4.2 Research Data

This research component used the Victorian annual bus inspection outcomes as an indicator for roadworthy condition (See Section 3.5 for further details of the data). There were 24,310 inspection records collected during the research period (2014-2018), with each record containing 14 indicators corresponding to each of 14 bus components. The indicators were binary coded with the value 1 depicting failure and 0 representing pass. The inspections originated from 234 bus operators, and the following operational characteristics were obtained: fleet size, location of operation, and service type.

4.3 Explorative Analyses

4.3.1 The Likelihood of Component Failure

Table 4.1 provides inspection failure rates for the 14 bus components. The levels of the safety risk on the most left column (high, medium and low) associated with different bus components were assigned by the state safety regulator (TSV)[1], which identifies trends such as "buses that fail one or more of the seven components of high safety risk" as the basis for regulatory enforcement.

Table 4.1 Failure rates of bus components during annual bus inspections for the period 2014-2018 in Victoria, Australia

Level of safety risk	Bus components inspected	Failure rate (%)
	Overall	17.9
	Components of high safety risk	15.9
High	Steering & Suspension	6.8
	Body & Chassis	6.2
	Engine & Driveline	5.0
	Brakes	4.1
	Brake performance	1.5
	Wheels & Tyres	1.2
	Seats & Seatbelts	3.1
Medium	Lamps, signals & reflectors	5.9
	Windscreen & Windows	1.6
	Windscreen Wipers & Washers	1.3
	Parking brake	0.6
Low	Exhaust emission controls	1.3
	Other items	4.4
	Modifications	0.2

During the four-year period, 18 percent of bus annual inspections failed at least one component, with around one in six (nine out of ten failed ones) failing at least one component of high safety risk. Some components were more prone to failure than others and issues with Steering & Suspension, Body & Chassis, Lamps, Signals & Reflectors, Engine & Driveline and Brakes were the most prevalent. The

[1] Sourced from TSV internal record.

results were similar to the outcome of National Heavy Vehicle Health Check in terms of components of vulnerability where the component with the highest rates of major non-conformity was associated with Brakes, followed by Steering & Suspension, Engine, Driveline & Exhausts, Lights & Reflectors, and Body & Chassis (National Heavy Vehicle Regulator, 2017).

4.3.2 Magnitude & nature of failure

Table 4.2 provides the number of inspections with different number of failed components and Figure 4.1 shows the proportion of inspections with different numbers of failed components. Among the failed inspections, around one-third failed one component, another 30 percent failed two, one fifth failed three and about 10 percent failed four, with the remaining 10 percent failed at least five components. There were some variations in terms of the magnitude of failures.

Table 4.2 The distribution of inspections within different number of failed components

Number of failed components	Number of inspections	Percentage (%) Within failure	Cum percentage (%) Within failure
0	19,948	82.1	n/a
1	1,389	31.84	31.84
2	1,325	30.38	62.22
3	847	19.42	81.64
4	425	9.74	91.38
5	195	4.47	95.85
6	96	2.20	98.05
7	41	0.94	98.99
8	25	0.57	99.56
9	6	0.14	99.7
10	4	0.09	99.79
11	3	0.07	99.86
12	2	0.05	99.91
14	4	0.09	100
Total	24,310	100	

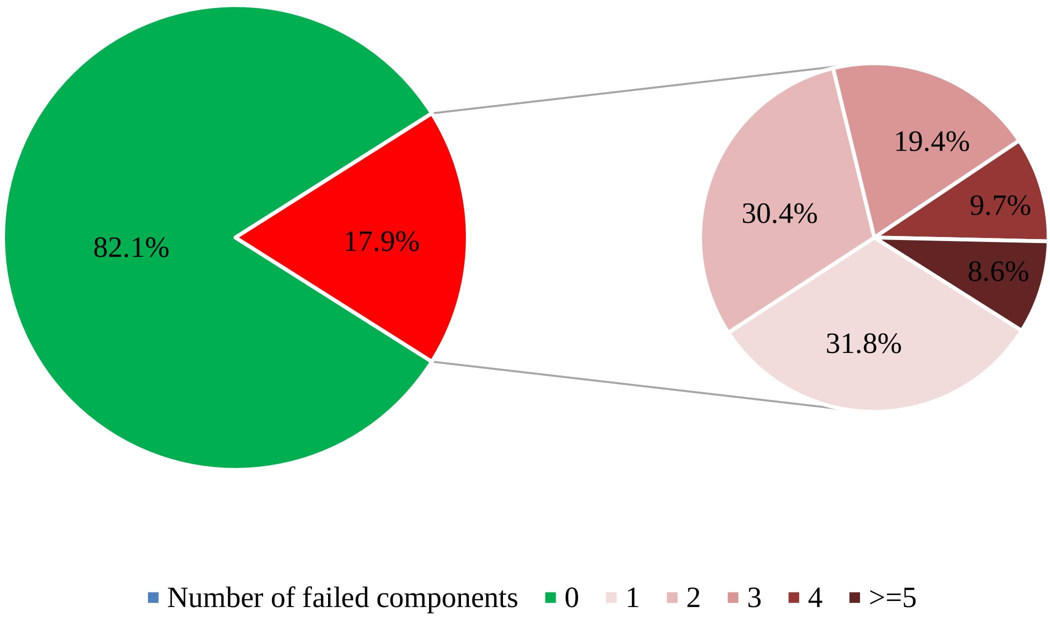

Figure 4.1 The proportion of inspections with different number of failed components

For inspections with the same number of failed components, different combinations were observed. A Venn diagram was adopted to illustrate the varying combinations of component failure. Figure 4.2 presents the combinations among five components and the numbers labeled in each segment represent the number of inspections with the respective combination of component failure. It clearly demonstrates the complexity of failures.

Both the magnitude (number) and the nature of failures elucidated their heterogeneity. To attain a more explicit understanding of the failures, Latent Class Analysis (LCA) was employed to identify distinct and meaningful patterns of failure. This analysis is described below.

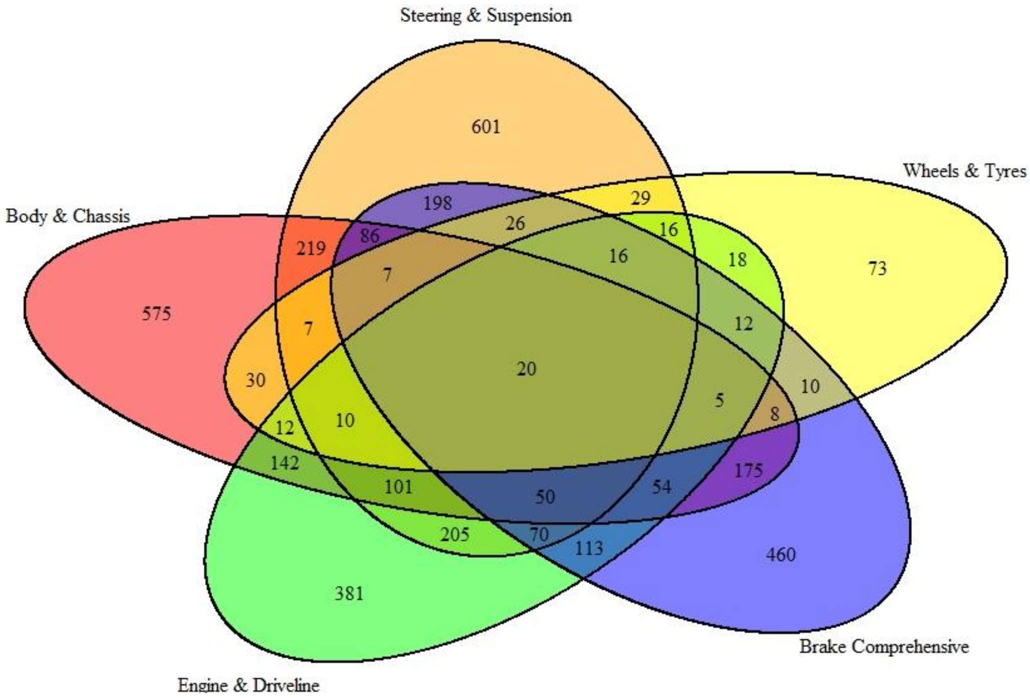

Figure 4.2 Venn diagram demonstrating the nature of inspection failures

4.4 Latent Class Analysis

Latent class analysis (LCA) is a probabilistic approach which describes the distribution of the data to extract distinct clusters (latent classes) of units that are homogenous with respect to the observed categorical variables (Clark & Muthén, 2009; McCutcheon, 1987; Mutz, Bornmann, & Daniel, 2013; Sasidharan, Wu, & Menendez, 2015; Vermunt, 2003). The observed categorical variables are referred to as 'latent class indicators' (Muthén & Muthén, 2012).

In this case, let Y_{ijk} denote the response of inspection i of operator j on component k; the number of components by K; a particular response on component k by S_k. The full vector of the response of inspection i by operator j is denoted by Y_{ij} and a possible response pattern by s. The latent class variable is denoted by X_{ij}, a particular latent class by t, and the number of latent classes by T. The probability structure defining a LC model can be expressed as in Equation (4.1): the probability of observing a particular response pattern $P(Y_{ij} = s)$ is a weighted average of class-specific probabilities $P(Y_{ij} = s|X_{ij} = t)$.

$$P(Y_{ij} = s) = \sum_{t=1}^{T} P(X_{ij} = t)\, P(Y_{ij} = s | X_{ij} = t)$$

$$= \sum_{t=1}^{T} P(X_{ij} = t) \prod_{k=1}^{K} P(Y_{ijk} = S_k |\, X_{ij} = t) \quad (4.1)$$

$P(X_{ij} = t)$: the probability that inspection *i* of operator *j* belongs to latent class *t*

$P(Y_{ijk} = s_k |\, X_{ij} = t)$: the probability of observing the response S_k on component *k* given the inspection concerned belongs to latent class *t,* therefore also referred to as conditional response probability.

4.4.1 Single level LCA

In the context of a single-level LCA with the assumption of local independence, the weight $P(X_{ij} = t)$, and the class specific probability $P(Y_{ijk} = s_k |\, X_{ij} = t)$ can be expressed as follows.

$$P(X_{ij} = t) = \frac{exp(\gamma_t)}{\sum_{t=1}^{T} exp(\gamma_t)} \quad (4.2)$$

$$P(Y_{ijk} = s_k |\, X_{ij} = t) = \frac{exp(\beta_{S_k t}^{k})}{\sum_{r=1}^{S_k} exp(\beta_{rt}^{k})} \quad (4.3)$$

4.4.2 Multilevel LCA

Taking into consideration the fleet setting, inspections are clustered within operators, which violates the local independence assumption (Vermunt, 2003). To accommodate the multilevel structure and resultant within-operator correlation and between-operator heterogeneity, the multilevel LCA approach was adopted.

The underlying assumption of multilevel LCA is that the probability of belonging to a certain lower-level response pattern may differ across the operators. The most general multilevel LC model assumes that all model parameters are operator specific. Therefore, Equation (4.2) can be written as follows.

$$P(X_{ij} = t) = \frac{exp(\gamma_{tj})}{\sum_{t=1}^{T} exp(\gamma_{tj})} \quad (4.4)$$

Such an operator specific approach can be problematic. Operator specific estimates have to be obtained for certain model parameters and the number of parameters to be estimated increases rapidly with the number of operators. Furthermore, operators with a small number of inspections may make the estimates volatile. Therefore, in accordance with Vermunt (2003), both the parametric and non-parametric approaches were explored.

4.4.2.1 Nonparametric vs parametric approach

The parametric approach specifies a normal distribution for the deviations of higher-level units (in this case, operator) from the overall parameter value. However, this distributional assumption is strong, and the interpretation of the effects of higher-level units is abstract (Asparouhov & Muthen, 2008; Vermunt, 2003). The nonparametric approach instead creates a latent class variable for the higher-level units (operators) in addition to the latent class variable for the lower-level units (inspections), relaxing the strong distributional assumptions and reducing the computation burden (Asparouhov & Muthen, 2008; Fagginger Auer, Hickendorff, Van Putten, Béguin, & Heiser, 2016; Vermunt, 2003). In addition, the generation of latent classes of higher-level units (operators) allows for a substantive interpretation of meaningful outcomes at the higher level (operator). The performance of the parametric and nonparametric models has been compared and the nonparametric approach has been found to generally produce more accurate recovery of the underlying latent structure of the data at both levels (Finch & French, 2014). Consequently, this study adopted the nonparametric approach.

In the nonparametric approach, there are not only latent classes of lower-level units (inspections), but also latent classes of higher-level units (operators) sharing the same parameter values. Let W_j denote the higher-level latent class variable and m a possible response. In the nonparametric approach, the latent class probability in Equation (4.4) can be expressed as follows.

$$P(X_{ij} = t | W_j = m) = \frac{exp(\gamma_{tm})}{\sum_{t=1}^{T} exp(\gamma_{tm})} \quad (4.5)$$

Regarding the conditional probabilities, the assumption implied in Equation (4.3) is that conditional probabilities do not depend on the higher-level unit. That is, individuals in a certain lower level latent class behave the same way irrespective of the higher level latent class to which the individual belongs (Mutz et al., 2013). However, it may happen that individuals belonging to different higher level latent classes respond to certain items in a different manner, a phenomenon that is referred to as item bias (Vermunt, 2003). In the nonparametric approach, item bias can be dealt with by allowing the conditional probabilities to depend on the higher-level latent class.

$$P(Y_{ijk} = S_k | (X_{ij} = t, W_j = m)) = \frac{exp(\beta^k_{S_k tm})}{\sum_{r=1}^{S_k}(\beta^k_{rtm})} \quad (4.6)$$

More detailed illustrations of the model can be found in Vermunt (2003) and Henry and Muthén (2010).

4.4.2.2 Selection of the number of latent classes

Summarising the literature, the number of latent classes should be selected to strike a balance amongst fit, parsimony, and interpretability (Chung, Flaherty, & Schafer, 2006; Stamovlasis, Papageorgiou, Tsitsipis, Tsikalas, & Vaiopoulou, 2018).

In terms of model fit, the Bayesian Information Criterion (BIC) has been suggested as a good indicator and performs better than other information criteria in clustering contexts (Allison, Adlaf, Irving, Schoueri-Mychasiw, & Rehm, 2016; Geiser, 2012; Henry & Muthén, 2010; Hsieh, Yang, Yang, & Yang, 2013; Nylund, Asparouhov, & Muthén, 2007; Stamovlasis et al., 2018). Lukočienė, Varriale, and Vermunt (2010) recommended AIC3 and BIC(K) (BIC based on the higher-level sample size) as the preferred measures for simultaneously deciding about the number of LCs at both the higher and lower level, which have been adopted in several applications (Fagginger Auer et al., 2016; Mutz et al., 2013). In general, the lower the value of these ICs, the more parsimonious the model is, the better it is. When analyzing large samples, however, the information criteria often do not reach a minimum value with an increasing number of classes (Bijmolt, Paas, & Vermunt, 2004; Sasidharan et al., 2015). In that case, the percentage of reduction in the information criteria between competing models may assist in deciding the number of clusters (de Oña, López, Mujalli, & Calvo, 2013; Sasidharan et al., 2015).

Entropy summarizes how well the latent classes are distinguished and makes a good indicator of class separation (Lukočienė et al., 2010). Entropy values range from 0 to 1, with higher values indicating clearer distinctions among the latent classes and a high level of classification certainty (Allison et al., 2016; Mutz et al., 2013).

Last but not least, with the motivation of applying latent class model being to identify meaningful groups of units, the interpretability of the model is vital and has been an important consideration in model selection (Allison et al., 2016; Henry & Muthén, 2010; Tomczyk, Hanewinkel, & Isensee, 2015).

4.4.2.3 Three-step sequential strategy

To identify the best-fitting model, the three-step sequential modeling strategy was used (Fagginger Auer et al., 2016; Henry & Muthén, 2010; Lukočienė et al., 2010; Mutz et al., 2013). In the first stage, the multilevel structure was ignored, and the 14 components were used as latent class indicators to estimate a series of single-level LC models to determine the number of latent classes at the inspection-level. In the second stage, the multilevel structure was account for, and a series of multilevel LC models were estimated. In these models, the number of inspection-level classes was based on the best fitting LC model from the previous stage, and models with different numbers of operator classes were estimated to determine the optimal number of operator-level LCs. In the third stage, the variation of the number of inspection-level classes upon the specification of the operator level was examined. This was accomplished by estimating a series of models with the number of operator-level classes taken from the second stage, and the number of the inspection-level classes varied. The models were estimated in Mplus 8.2, using maximum likelihood (ML) estimation and the Expectation Maximization (EM) algorithm (Muthén & Muthén, 2012). Model comparison, selection, and evaluation were based on the criteria illustrated in Section 4.4.2.2.

4.5 Results of Latent Class Analysis

4.5.1 Single Level LCA

The modeling procedure started with the single-level LCA, ignoring the nesting of inspections within operators. A series of single-level LCA models were estimated to determine the number of latent classes at the inspection-level (the upper part of Table 4.3, marked in blue). The lowest value of the BIC was found for the four-class solution. The LCA model with four inspection-level latent classes was then further examined and compared with neighbouring models. The substantive interpretation of the four-class solution (as described below) offered more insightful results than the three-class one. The five-class solution had the smallest class consisting of 11 observations only, which was considered too small to be generalizable to the broader population. The entropy for the four-class solution was 0.856, indicating satisfactory class separation. Therefore, the four-class solution was determined as the best fitted inspection-level LCA model.

Table 4.3 Fit statistics for exploratory LC model specifications

	Number of inspection-level classes			
	2 Class	3 Class	4 Class	5 Class
Single-level LCA model				
No. of free parameters	29	44	59	74
Log-likelihood	-36446.25	-36161.07	-36073.61	-36012.7
AIC3	72979.498	72454.132	72324.224	72247.34
BIC	73186.195	72767.742	72744.747	72774.78
BIC(K)	73051.194	72562.912	72470.088	72430.29
Entropy	0.885	0.897	0.856	0.87
Nonparametric MLCA model				
2 operator-level classes				
No. of free parameters		47	63	79
Log-likelihood		-35110.8	-34968.3	-34905.3
AIC3		70362.56	70125.65	70047.69
BIC		70697.55	70574.69	70610.76
BIC(K)		70478.75	70281.41	70243
Entropy		0.924	0.900	0.903
3 operator-level classes				
No. of free parameters		50	67	84
Log-likelihood		-34782.9	-34662.7	-34597.8
AIC3		69715.75	69526.38	69447.7
BIC		70072.13	70003.92	70046.41
BIC(K)		69839.37	69692.02	69655.37
Entropy		0.921	0.896	0.901
4 operator-level classes				
No. of free parameters		53	71	89
Log-likelihood		-34627.2	-34476.3	-34407.3
AIC3		69413.48	69165.7	69081.56
BIC		69791.23	69671.75	69715.91
BIC(K)		69544.51	69341.23	69301.6
Entropy		0.911	0.902	0.905
5 operator-level classes				
No. of free parameters		56	75	94
Log-likelihood		-34557.7	-34383.9	-34281
AIC3		69283.4	68992.85	68844.02
BIC		69682.54	69527.42	69514.01
BIC(K)		69421.85	69178.27	69076.42
Entropy		0.914	0.908	0.905

Note: AIC3=3* *df* -2 * LL, BIC= *df* *In(n)-2 * LL, BIC(K) = *df* * ln(k)-2 * LL, *df* is the number of free parameters in the model and LL is the Log-likelihood.

4.5.1.1 The likelihood of component failure within each failure pattern

Figure 4.3 depicts the class specific probabilities, which provide valuable information to interpret the identified latent classes.

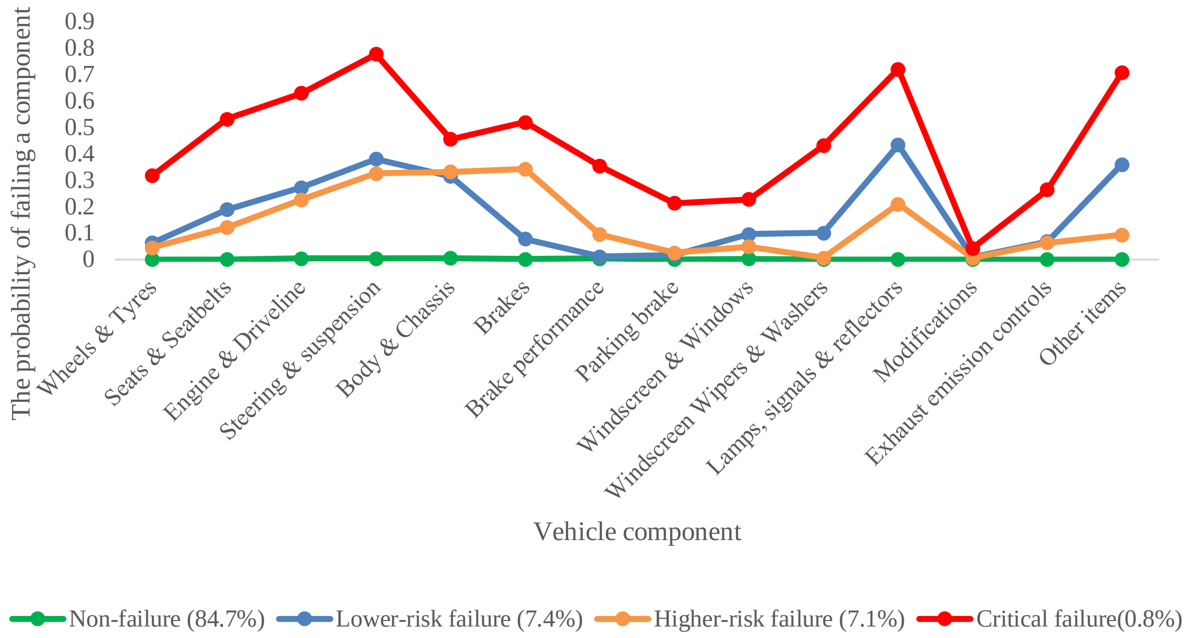

Figure 4.3 Profile plot of the four-class solution at the inspection level

Class 1, which represented 85 percent of the inspections, passed almost all the components and was thus referred to as 'non-failure'. Classes 2 ('Lower-risk failure') and 3 ('Higher-risk failure'), each accounting for around 7 percent of the inspections, had similar patterns in the endorsement of most of the components of high safety risk (Wheels & Tyres, Engine & Driveline, Steering & Suspension and Body & Chassis). Class 3 was characterized by a relatively higher probability than Class 2 of failing indicators relating to brakes (Brake and Brake performance), which are identified as dominant mechanical defects contributing to crashes (Section 2.3.1) and therefore of a higher safety risk, while Class 2 was characterized by a relatively higher probability than Class 3 of failing components of lower safety risk (i.e. Lamps, Signals & Reflectors, Other items). Class 4, accounting for only 0.8 percent of the inspections, had the highest probability of failing every component and was designated as the 'Critical failure' class.

4.5.1.2 Magnitude of failures within each failure pattern

The number of components failed within each pattern helps justify the relevance and facilitate the understanding of the identified patterns (Table 4.4).

Within the non-failure class, 96.8 percent of the inspections did not fail any of the components. The 'Lower-risk failure' and 'Higher-risk failure' classes generally sustained between one and four components (92.9%, 96.2% respectively). The majority of the inspections (97.3%) belonging to the 'Critical failure' class failed at least five components. The identified failure patterns achieved a satisfactory degree of internal homogeneity.

Table 4.4 The magnitude of failure within four inspection-level latent classes

	Inspection-level latent class				
Number of failed components	Non-failure	Lower risk	Higher risk	Critical	Total
0	96.8%				
[1,4]	3.2%	92.9%	96.2%	2.7%	
>=5		7.1%	3.8%	97.3%	
Total	20,599	1,810	1,714	187	24,310

4.5.2 Multilevel LCA

Multilevel LC models with latent structures of up to five operator classes were fitted to the data (marked in red in Table 4.3). The fit statistics showed that adding a multilevel structure significantly improved model fit, signifying considerable within-operator correlations of inspection outcomes.

Among these models, AIC3, BIC, and BIC(K) drastically declined from two to four operator classes then began to level off (the reduction on ICs from four to five class solution was comparatively negligible), as illustrated in Appendix A: Figure 4.8. As a result, the four-class solution was chosen for the higher-level model.

Changes in the number of inspection-level classes due to the inclusion of operator-level latent classes were also examined. The neighbouring models with three and five inspection-level classes were estimated. The number of inspection-level classes remained unaltered: the model with four inspection-level classes appeared to be superior, showing the lowest BCI, a substantial decline in AIC3 and BIC(K) over the model with three inspection-level classes and a negligible decline in AIC3 and BIC(K) over the model with five inspection-level classes.

The final model included four inspection-level latent classes and four operator-level latent classes. The entropy for the model was 0.902, indicating good classification qualities and high confidence in the latent class membership.

4.5.2.1 Failure compositions among operator types

The composition of the four failure patterns within each of the four operator types is presented in Figure 4.4. The colours in the bar chart match the colours representing the different failure patterns in Figure 4.3.

The four operator types showed substantial heterogeneity in their compositions of failure patterns.

Operator Type 1, which accounted for around a quarter of the operators, comprised the overwhelming majority (95.4%) as non-failures and was clearly the best-performing class. Type 2 operators, representing 29 percent, maintained a lower, but still relatively high proportion of non-failures (84.9%) and was characterized by a one in ten chance of having a 'higher-risk failure'. Inspection outcomes from Type 3 operators had a three in ten chance of being a failure, albeit mostly in the 'lower-risk failure' class. Type 4 operators, the smallest category in terms of the number of operators (16%), were characterized by the statistically significant lowest proportion of non-failures and the highest (also significant) proportion of critical failures and were clearly the worst-performing group.

The probability of an inspection following a specific failure pattern varied significantly among the operator types, which endorsed the application of the multilevel approach.

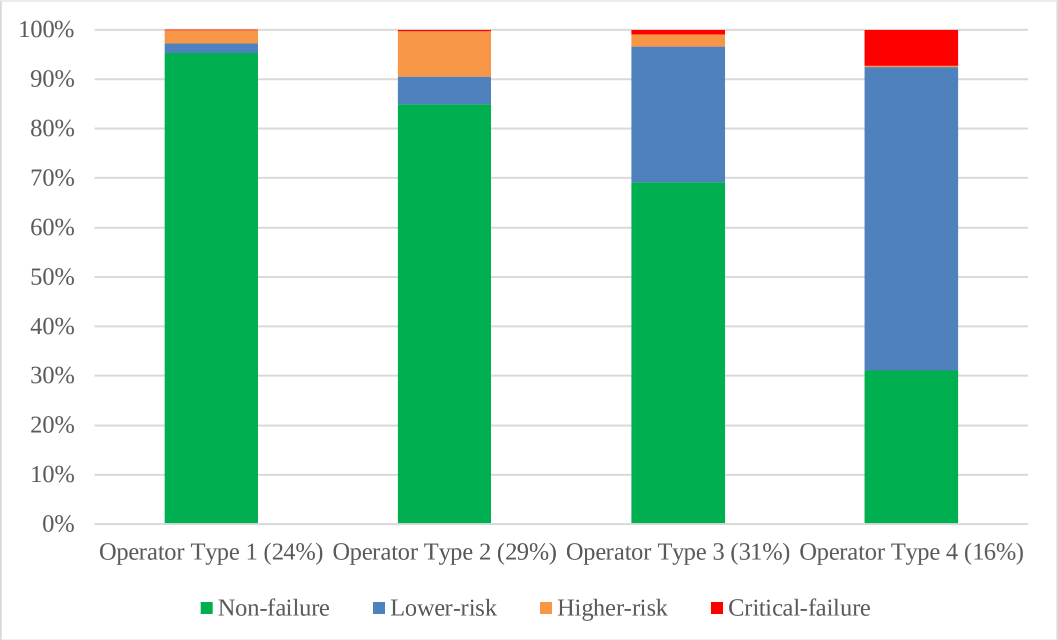

Figure 4.4 Distribution of failure patterns within operator type

Note: 24,310 inspections within 234 operators

4.5.2.2 Profiles of operator types

The operational characteristics of the four operator types including fleet size, location of operation, and service type were examined and compared, with the results shown in Table 4.5 and Figures 4.5 -4.7.

Table 4.5 The profiles of operator types

	Type 1	Type 2	Type 3	Type 4	Total
Size					
Large (>50)	12	16	4	0	32
Medium (20-50)	8	10	10	6	34
Small (<=20)	37	41	59	31	168
Service type					
Route	16	23	8	7	54
Tour & Charter	22	30	39	22	113
School & Other	19	14	26	8	67
Location					
Metropolitan	14	12	18	15	59
Regional	43	55	55	22	175

A higher proportion of Type 1 and 2 operators were large and route operators while a higher proportion of Type 3 and 4 operators were small and tour & charter operators.

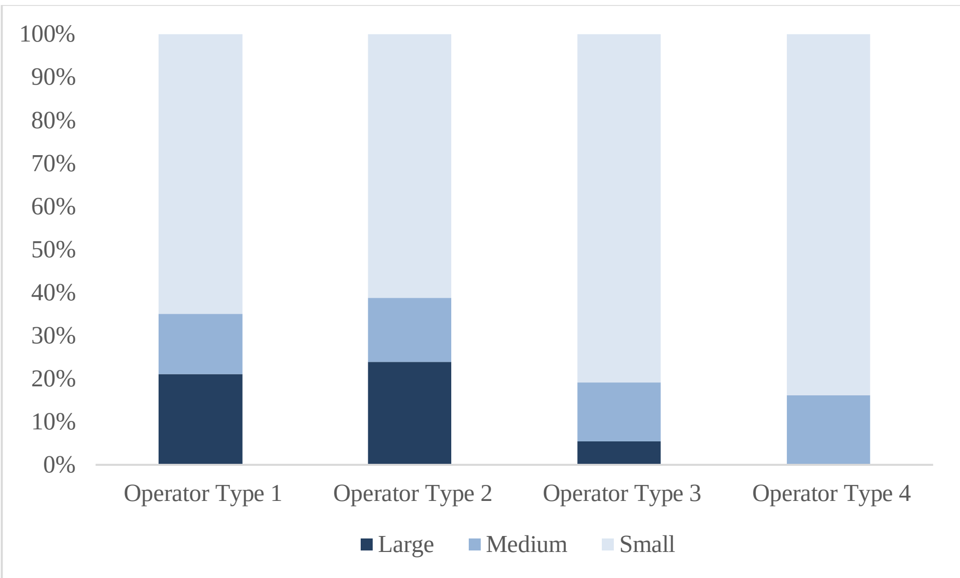

Figure 4.5 Size distribution within operator types

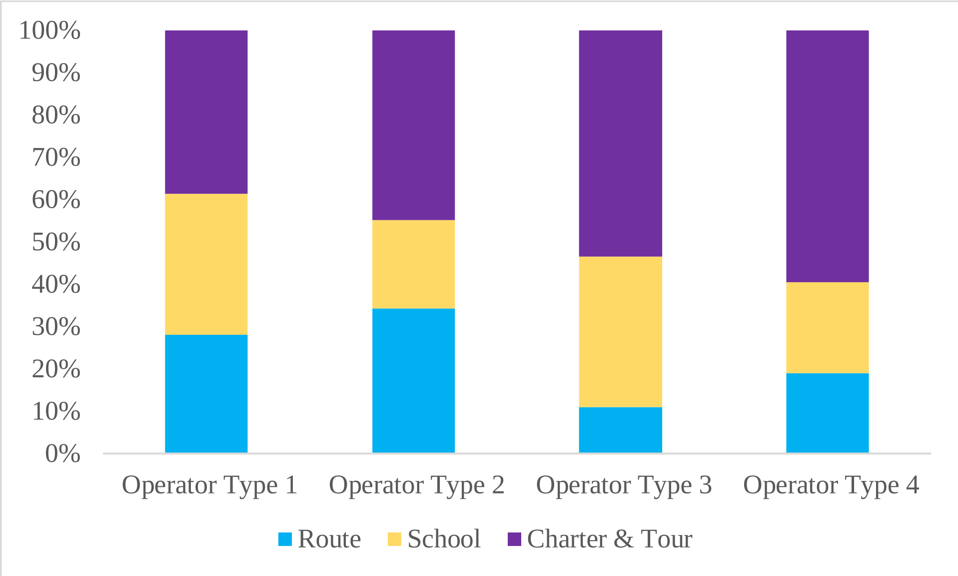

Figure 4.6 Service type distribution within operator types

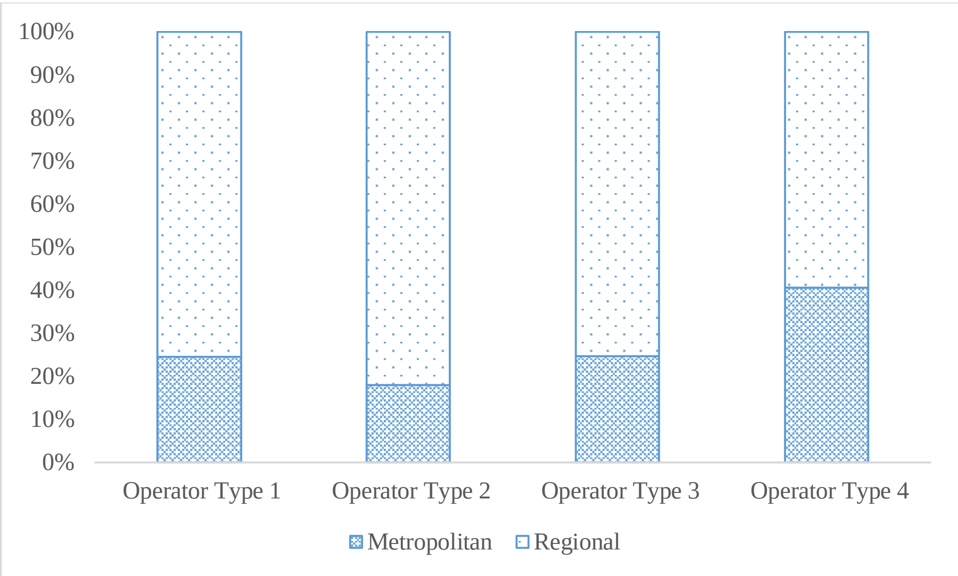

Figure 4.7 Operating location distribution within operator types

The tests of association suggested that there were statistically significant associations between operator type and size (Fisher's Exact Test, $p = 0.000$), and service type (χ^2 (3) = 11.9779, $p = 0.007$) while no significant association with location (χ^2 (3) = 6.5295, $p = 0.089$) was found. Post hoc tests examined the differences between any two operator types and Bonferroni corrections (0.05/6=0.008) were applied to correct for the multiple comparisons (McDonald, 2009) (refer to Appendix A: Table 4.7 for details).

As presented in Figure 4.5 - 4.7 and Table 4.6, a higher proportion of Type 1 and 2 operators were large operators compared with Type 4, while a higher proportion of Type 2 operators were route operators compared with Type 3.

Table 4.6 Post hoc tests

Significant p-values	Type 1	Type 2	Type 3	Type 4
Type 1				
Type 2	*None significant*			
Type 3	*None significant*	Size[1] Service type[2]		
Type 4	Size[1]	Size[1]	*None significant*	

[1]Collapsed as Large vs Non-large
[2]Collapsed as Route vs Non-route

It is noted that no significant differences in any of the characteristics were identified between Types 1 and 2, and between Types 3 and 4. The fact that the discrepancy between Types 1 and 2, and between Types 3 and 4 could not be fully accounted for by the variables collected suggests other, non-modeled, factors in play.

There is speculation that Type 1 operators probably do pre-annual inspections, including washing and inspecting the bus before it is presented and Type 4 operators do not. As quoted from fleet managers during a focus group discussion (Victorian bus operators, 2019):

"We have two designated guys that work in, do pre or post-annual inspections and because they're doing it constantly, they focus and they think of small things a normal mechanic would let it slide, their eyes are trained to go to that area. So, we have a pretty good success rate, but we put a lot of work into that. It just doesn't happen overnight".

"Like, as I said, when we've missed washing a bus, it's so much more likely to be picked on, nothing to do with washing it, but it's more likely to get an issue than when we've been able to clean them all and they're perfectly clean. Because that's just inspectors don't like looking at dirty buses."

The inspection results can also be affected by the frequency of inspector visits and the quantity of buses presented for one visit. Imagine that a depot needs to get 48 buses through annual inspections per year. Compared with preparing 12 buses each time for a quarterly visit, 4 buses for a monthly visit will grant a higher pass rate. It can be overwhelming to prepare large numbers of buses ready for inspections at the same time. Therefore, operators tend to schedule fewer inspections for each visit, allowing themselves more time to prepare fewer buses more regularly. Additional benefits of more frequent visits include stronger relationships with inspectors and increased experience and practice in preparing vehicles for annual inspections.

To summarise, factors like the practice of pre-annual inspection, frequency of inspector visit, and the relationship with inspectors may account for the annual inspection outcomes.

4.6 Discussion

This study demonstrated the first application of multilevel latent class analysis to large-scale annual bus inspection data, which generated classes of relevance at both inspection and operator levels, and enhanced the understanding of bus roadworthy performance. This approach proved to be an appropriate analysis addressing the challenges posed by the data structure. A sufficiently large sample (over 25,000 annual inspections) made it possible to capture the small latent class of unique significance (critical failure) and the 238 geographically dispersed operators ensured a heterogeneous sample of operators and inspections.

There are some known anomalies with the way failures of vehicle components are recorded or collected. For example, while a severe deterioration of the integrity of the bus is recorded as failing Body & Chassis, the same failure can also result from the vehicle missing a sticker. This way of recording failures irrespective of their implications on vehicle reliability and safety can bias the failure patterns identified. It is recommended that failures be further distinguished based on their safety implications (e.g. minor, major, critical) and uniformly recorded across Victoria, as is already the practice in NSW and the largest bus inspector in Victoria. Future research can benefit from the accuracy of the data and generate enhanced and more precise associations between failure patterns and safety implications.

4.7 Conclusion

This chapter presented the development of a sophisticated analytical approach to investigating the roadworthy condition of Victorian buses, which provide unique methodological contributions to the research field. Explorative analyses on the likelihood and magnitude of failures were undertaken and illustrated the heterogeneous nature of inspection failures. The multilevel latent class analysis was applied, which addressed the hierarchical data structure and contributed to an innovative understanding of the roadworthy performance. Four inspection failure patterns were identified, non-failure, lower-risk, high-risk and critical failure respectively. The likelihood and magnitude of the four failure patterns were examined, which verified the relevance of the results and enriched the context of failure. Four operator types were identified, demonstrating varying compositions of failure patterns and levels of performance. The profiles of the operator types were inspected, which enhanced the understanding of operator type and effect on vehicle roadworthy condition.

The findings inform safety regulators of evidence-based regulations, including tackling operators of specific failure patterns. Limitations included the neglect of the safety implication of failures in the inspection results collected and the inadequacy of explanatory power to operator types. Proposed directions for future research included incorporating the safety implication of component failure when generating failure patterns, and in-depth investigations on operators to uncover the merits or demerits that make certain operators at advantage or disadvantage.

Chapter 5 EVALUATING CURRENT INSPECTION AND MAINTENANCE PRACTICES OF AUSTRALIAN BUS OPERATORS

5.1 Introduction

As described in Section 2.4, in a bus transit system, operators take the role of managing and implementing a set of inspection requirements and are therefore ultimately responsible for bus roadworthiness. As was shown in the previous chapter, bus roadworthy condition varies significantly among operators and therefore, even within the same regulatory environment, it seems likely that inspection practices differ substantially. However, little is known about current inspection practices, nor the influencing factors. In addressing the knowledge gaps, this chapter centers on investigating the self-reported inspection practices of bus operators in Australia and identifying the influential factors.

The bulk of the work presented in this chapter originated in our research paper: Qiu, Logan, Oxley, and Lowe (2018).

The chapter starts with an introduction to the research context, including the structure of bus maintenance management and the factors influencing inspection practices. This is followed by the description of the questionnaire design, data collection, and sample. The descriptive analyses of the operational characteristics, inspection practices, and perceptions are then presented, as well as the interactions among them. This chapter closes with a discussion of the results and conclusions.

5.2 Research Context

5.2.1 The structure of bus maintenance management

As illustrated in Section 2.4, in general, there are three typical levels of bus inspection in Australia, designed to complement one another. Details on them ('pre-trip inspection' (first), 'time-distance based inspection' (second), and 'mandatory, independent inspection' (third)) have been presented in Section 2.4 and will not be expanded upon here.

5.2.2 Factors influencing inspection practices

Apart from the operational characteristics reviewed in Section 2.4.2.2, the perceptions of the importance, productivity, and financial aspects of inspections have a direct interrelationship with inspection practices. In general, positive perceptions of the benefits of vehicle inspections may encourage preventative inspections while negative perceptions may discourage operators from conducting inspections properly. It is therefore worth briefly outlining the potential perceptions operators may have on inspections.

In various jurisdictions, the importance of inspections has been emphasized by state safety regulators and conveyed to operators (Bus & Coach Association NSW, 2011; Bus Safety Victoria, 2017b; Canadian Council of Motor Transport Administrators, 2014).

Regarding productivity, on one hand, inspections help eliminate mechanical anomalies, minimize interruptions to bus operations, boost vehicle availability, and thus maximize productivity. On the other, while it is desirable to perform inspections when the buses are not in service, there is a productivity cost for those inspection activities that interrupt or suspend operation and impair production capacity (e.g. time pulled out of service for maintenance) (Haghani & Shafahi, 2002).

Inspections play a critical role in helping to protect buses from breaking down and increasing vehicle longevity, which is financially beneficial (Beruvides et al., 2009; Haghani & Shafahi, 2002). However, the costs of an inspection, including labour (e.g. staff doing pre-trip inspections, conducting periodic maintenance and taking vehicles for mandatory, independent inspections), materials and supplies, service fees (e.g. outsourced maintenance) and the like account for the second highest expense category after vehicle operations in a typical transit system (Bladikas & Papadimitriou, 1986) and can make up approximately 20 percent (vary with time and size of operation) of the total operating expenses (Purdy & Wiegmann, 1987).

5.3 Methods

5.3.1 Questionnaire descriptions

To achieve the research aim, the study sought to answer the following research questions: (a) What is the nature of current inspection practices? (b) How do the various operators inspect their buses? (c) How are inspections perceived by operators and whether/how are these perceptions associated with inspection practices? The questionnaire was designed comprising three sections: Section I collected the characteristics of bus operations, including state, ownership, contract, location of operation, service type, number of buses, number of drivers, number of maintenance staff, and number of maintenance bays. Section II asked about the practices of the three vehicle inspection types, including the scheme, schedule, and personnel. Questions were designed to probe the existence of practices and assess the implementation of the procedures. Section III investigated the perceptions of the three inspection types used in Australia and operators were asked to rate the perceived importance, productivity, and financial impact to them of each. A five-point Likert Scale was used to specify the responses.

The questionnaire items underwent a two-stage review process. The first stage involved a structure examination with a statistician to make sure the questions were properly structured to address the research questions. The second stage involved content validation with practitioners in the field, including safety regulators, directors, and fleet managers from several depots, who reviewed the items to assess the interpretability, clarity, fluency, and complexity of the questionnaire. The final questionnaire is presented in Appendix B.

5.3.2 Data collection and sample

Participants were recruited with the assistance of two stakeholder groups: professional bus associations in Victoria, Queensland, and South Australia, which are the industry representative bodies for accredited bus operators in those states; and Transport Safety Victoria, the government safety regulator of public transport in Victoria. The bus associations assisted by sending paper-based questionnaires to all their members (Victoria-410, QLD-168, and SA-26) and 157 responses (Victoria-111, QLD-35, and SA-11) were received within 3 months. The response rate of participants in each state is consistent with that of another questionnaire targeting bus operators in different states (Lowe, 2016). A further 19 responses were received through a link on the Transport Safety Victoria's website. A total of 171 responses (excluding five invalid responses) formed the sample, which was deemed adequate for undertaking statistical analyses to investigate the research questions outlined above.

5.4 Data Analyses and Results

A series of statistical analyses were performed in this study, using Microsoft Excel 2013 and SPSS Statistics 23.

5.4.1 Characteristics of operators

The vast majority (85.9%) of the respondents were either the director or manager of their operation and had an average of 18 years of experience in the position.

The distribution of key characteristics of operation is presented in Figure 5.1 and Table 5.1.

Respondents from VIC made up 71 percent of the sample, QLD 22 percent, and SA 7 percent. The overwhelming majority of the operators (94.2%) were family-owned, corresponding well with the nature of Australian bus operators overall (Lowe, 2016). Over four fifths (83.6%) provided a bus service under a contract with their state public transport authority. Nearly two thirds (65.5%) of the operators provided service in rural areas, and around one fifth (19.3%) provided regional service, with the remaining operating in metropolitan areas. Compared with the distribution of operators in the inspection dataset (Chapters 4, 6 & 7), the sample here had a higher proportion of rural/regional operators (85% vs 75%).

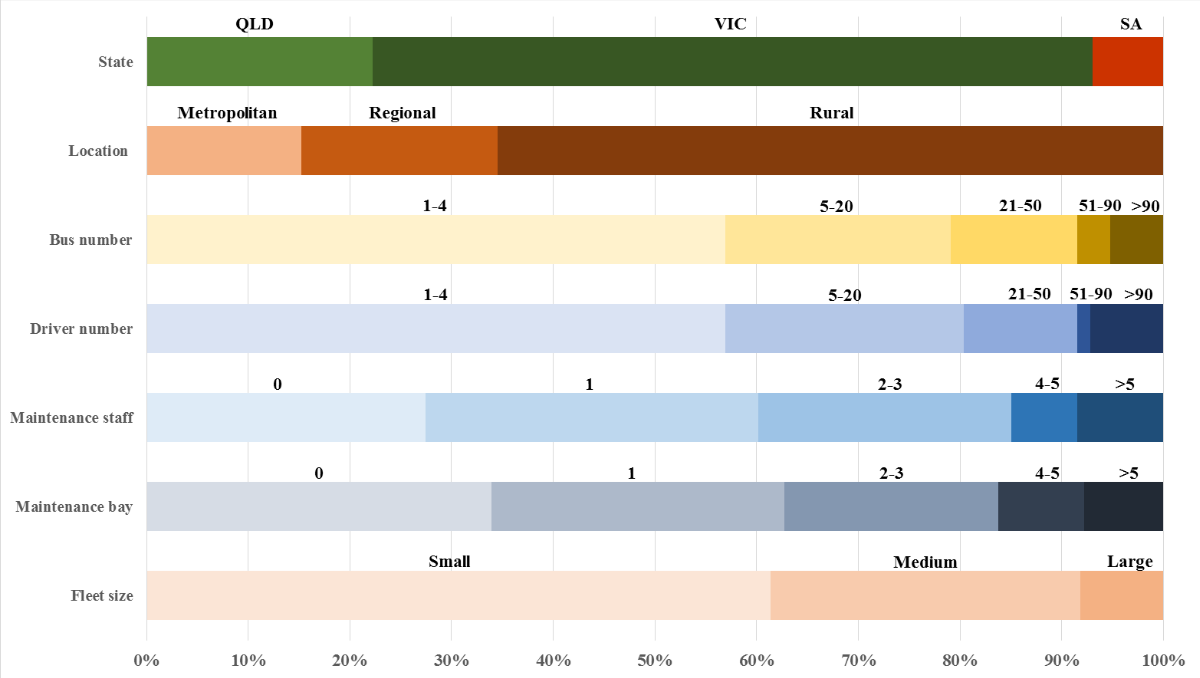

Figure 5.1 Characteristics of operators

The strong correlations between the number of buses, driver, maintenance staff, and maintenance bay formed the basis for the classification of operations into three groups. They are as follows:

- Small (no more than four buses/drivers and no more than one maintenance staff/bay)
- Medium (between five and 50 buses/drivers and between two and five maintenance staff/bays) and
- Large (more than 50 buses/drivers and more than five maintenance staff/bays) operators.

It is worth noting that the classification of operator size (between small and medium) is slightly different from the classification used in Chapters 4 and 6 due to the different sample compositions between this and the inspection data.

Half of the operators provided only one type of service, around one quarter provided two and the remainder provided at least three types of services. Among those who provided only one type of service, nearly 90 percent (89.5%) provided school service. For those who provided two types of service, school and tour & charter took up nearly three fifths (59.1%). Among those who provided at least three types of service, operators covering school and tour & charter accounted for the overwhelming majority (95.1%). In view of these patterns, bus services were classified into three categories: school but non tour & charter (53.2%), school and tour & charter (38.0%), and non-school (8.8%).

Table 5.1 Distribution of service type

<table>
<tr><th>Service Number</th><th>One (50.3%)</th><th>Ratio (%)</th><th colspan="2">Two (25.7%)</th><th>Ratio (%)</th><th>Three or More (24.0%)</th><th>Ratio (%)</th></tr>
<tr><td rowspan="5">Service type</td><td>School</td><td>89.5</td><td rowspan="3">School involved</td><td>Tour & charter</td><td>59.1</td><td rowspan="2">School and Tour & charter involved</td><td rowspan="2">95.1</td></tr>
<tr><td>Tour & charter</td><td>7.0</td><td>Route</td><td>20.5</td></tr>
<tr><td>Route</td><td>2.3</td><td>Other</td><td>11.3</td><td rowspan="2">Non-school</td><td rowspan="2">4.9</td></tr>
<tr><td>Other</td><td>1.2</td><td colspan="2">Non-school</td><td>9.1</td></tr>
<tr><td>Total</td><td>100</td><td colspan="2">Total</td><td>100</td><td>Total</td><td>100</td></tr>
</table>

Most of the characteristics examined above are likely to influence inspection practices, so to achieve a comprehensive understanding of the differences between operator groups, cluster analysis, which coordinates multiple characteristics, was applied to the data. A two-step cluster was selected to accommodate the categorical variables. Considering the predictor importance of the variables and aiming to maximize intragroup homogeneity and intergroup heterogeneity, a solution of three clusters was drawn, with cluster quality being good and the importance of all three predictors being larger than 0.7 (Location (1.00), Service type (0.96) and Fleet size (0.70)). Cluster 1 (38.6%) is mostly composed of non-metropolitan, medium, school and tour & charter operators. Cluster 2 (19.9%) mainly consists of metropolitan operators providing school and tour & charter or non-school service, which are of varying size. Cluster 3 (41.5%) is a group of small, rural, school but non-tour & charter operators. The clusters correspond to the industry's general rule of thumb and provide a multi-dimensional portrait of the operators. To facilitate further interpretations, the clusters are referred to as non-metropolitan median operators, metropolitan operators and rural, small operators, respectively.

5.4.2 Inspection practices

The practices of the three types of inspections are summarised in Table 5.2.

Table 5.2 Descriptive summary of inspection practices

Pre-trip	**Ratio (%)**	**Time-distance based**	**Ratio (%)**	**Mandatory, independent**	**Ratio (%)**			
Undertaken		**Undertaken**		**Aware**				
Yes	98.8	Yes	92.4	Yes	99.4			
No	0.6	No	5.3	No	0.6			
It depends	0.6	Don't know	1.7	**Guideline (170)**	VIC	QLD	SA	Total
Frequency (169)		It depends	0.6	State/NHVR only	55.8	42.1	83.3	54.7
Every departure from depot	27.2	**Schedule (158)**		Manufacturers' only	9.2	23.7	0.0	11.8
Every day	71.0	Manually	64.6	Manufacturers' & State/NHVR	20.8	10.5	16.7	18.2
Other	1.8	Computerized	19.0	Internal involved	11.7	15.8	0.0	11.8
Personnel (169)		By experience/ when necessary	8.2	Other	2.5	7.9	0.0	3.5
Bus driver only	85.8	School holiday	2.5	**Strong incentive (170)**	VIC	QLD	SA	Total
Maintenance staff/fueler only	4.7	Other	5.7	Agree	87.5	73.7	100.0	85.3
Combination[1]	9.5	**Personnel (158)**		Neutral	7.5	21.1	0.0	10.0
Duration (168)		Maintenance staff only	44.9	Disagree	5.0	5.3	0.0	4.7
1-5	33.9	Outsource only	34.2	**Proposed frequency (169)**	VIC	QLD	SA	Total
6-10	44.0	Owner/driver only	10.8	At least biannual	15.1	60.5	16.7	25.4
11-15	16.1	Combination[2]	8.2	At most annual	84.0	34.2	75.0	72.2
15-30	6.0	Other	1.9	Other	0.8	5.3	8.3	2.4

[1]Bus drivers and maintenance staff/fueler
[2]Both internal staff and outsource

5.4.2.1 Pre-trip inspections

It was evident that the vast majority of operators (98.8%) conducted pre-trip inspections, indicating that inspecting buses prior to the first passenger-carrying trip on each operating day (specified as either daily or every departure, depending on service type), as required by safety regulators, was a common practice amongst this industry sample. In most cases (95.3%), the bus driver took responsibility for pre-trip inspections. The duration varied significantly, with around one third (33.9%) spending no more than 5 minutes while some operators took up to 30 minutes.

5.4.2.2 Time-distance based inspections

While the majority of the respondents (92.4%) had a time-distance based inspection scheme in place, nine said they did not, with all of the non-conforming respondents being Victorian operators who claimed that this inspection type was not necessary for their fleet. For the three who admitted that they did not know, it may have been due to their unfamiliarity with the term "time/distance based inspections" which can be addressed as safety check, vehicle safety inspections (Bus Safety Victoria, 2017b), A, B, C, D inspection (Jardine & Hassounah, 1990) or Type 1, 2, 3, 4, 5 inspection (Haghani & Shafahi, 2002) in the bus industry. For those who conducted time-distance based inspections, nearly two thirds (64.6%) manually scheduled, around one fifth (19.0%) implemented a computerized recording and reminder system and 8.2 percent relied on either their experience or necessity (presumably subsequent to a breakdown or some obvious indication of a fault). Over one third (34.2%) of the operators outsourced (only) their time-distance based inspections to specialised maintenance & repair companies, 44.9 percent relied on maintenance staff in their depots only (internal) and in one out of 10 cases (10.8%), only owners/drivers (internal) took care of this inspection type, which were the typical 'man-and-his-bus' operators (Dodero, Casello, Molinero, & Cotera, 2013).

5.4.2.3 Mandatory, independent inspections

Mandatory, independent inspections were well acknowledged by the respondents, with the vast majority of operators (99.4%) being aware of these requirements. The majority of the participants stated that maintenance of the vehicle was completed to the state or national heavy vehicle specifications. Further, most operators from all jurisdictions (Fisher's Exact Test=6.395, p=0.114) agreed (85.3%) that this inspection type acted as a strong incentive for them to maintain their vehicles in a roadworthy condition. The inspection scheme, however, varied significantly across jurisdictions. SA operators mainly referred to state requirements/NHVR (National Heavy Vehicle Regulator) as the guideline while QLD operators were more likely to rely only on manufacturers' recommendations. QLD operators were significantly more likely to propose at least biannual inspections (60.5%) while VIC operators (84.0%) tended to suggest the interval should be no shorter than one year (Fisher's Exact Test=33.168, p=0.000), matching their current status.

5.4.3 Perceptions on inspection types

For each of the measures of perception (importance, productivity, and financial impact), the three inspection types were plotted as 100 percent stacked bars to illustrate the distribution of each inspection type and allow an intuitive comparison between them as shown in Figure 5.2.

Almost nine out of ten respondents thought that all three inspection types were either extremely important or very important, with time-distance based inspections perceived to be not as important (although this difference was not statistically significant). More respondents thought that inspections brought productivity gains, indicating the effect of inspections on maintaining vehicles in roadworthy condition, minimizing service interruptions and maximizing operation efficiency. Operators differentiated the financial impact of the three inspection types, with mandatory independent inspections being considered to cause the greatest financial impost (Friedman Test (χ^2 (2) = 54.986, p = 0.000), with post hoc tests), suggesting a need for improvement.

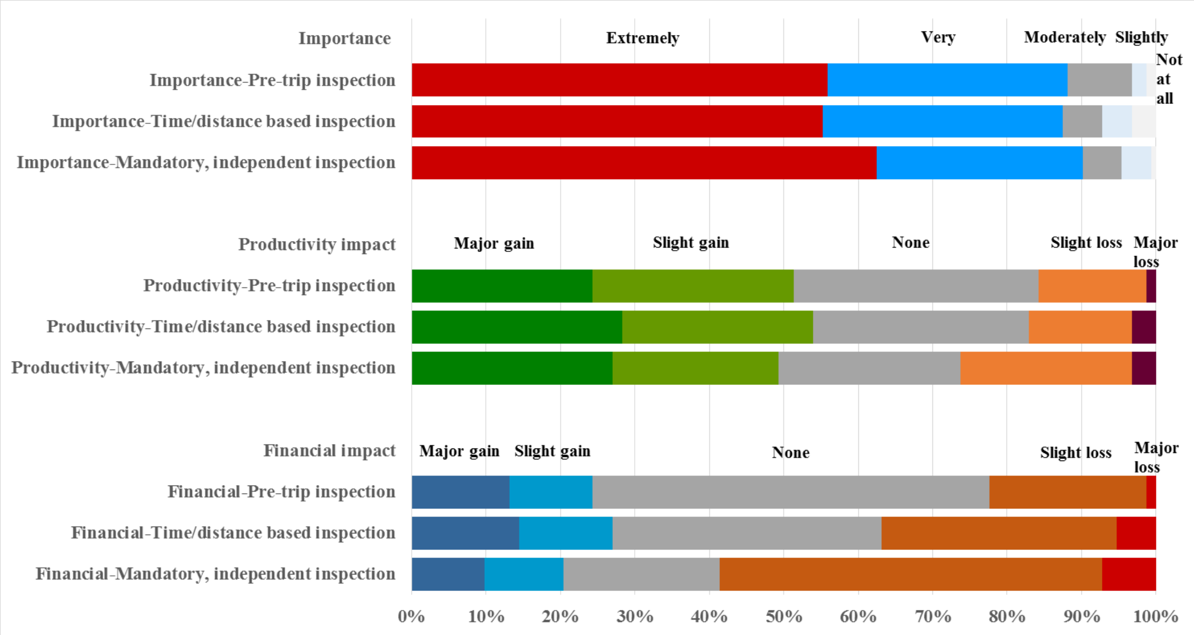

Figure 5.2 The perceived importance, productive and financial impact of the three inspection types

5.4.4 Interactions

The interactions between operational characteristics, inspection practices, and perceptions were examined. The identified associations were highlighted, as shown in Figure 5.3.

5.4.4.1 Characteristics and inspection practices

The inspection practices, particularly that of time-distance based type, varied among the different operator types, especially between small, rural operators and the others.

This group generally had no more than one maintenance staff member. Accordingly, they were significantly less likely to use maintenance staff or a vehicle refueler to carry out pre-trip inspections (4.3%) than were the metropolitan operators (29.4%) (Fisher's Exact test, p=0.001). Small rural operators were significantly more inclined to outsource their time-distance based inspections (60.3%) compared with metropolitan operators (15.6%) (Fisher's Exact Test=22.490, p=0.000) and non-metropolitan, medium operators (17.5%) (Fisher's Exact Test=25.537, p=0.000). These findings are consistent with those of the literature, which identified a lack of local inspection expertise and resources (Beruvides et al., 2009; Ng et al., 2012).

Small, rural operators were also significantly less likely to schedule time-distance based inspections with a computerized system (1.6%) compared with metropolitan operators (46.9%) (Fisher's Exact Test=32.176, p=0.000) and non-metropolitan, medium operators (22.2%) (Fisher's Exact Test=19.520, p=0.000). Interestingly, more than eight out of 10 (81.0%) of small, rural operators manually scheduled their inspection.

The associations identified above are marked as red dash-dotted lines in Figure 5.3.

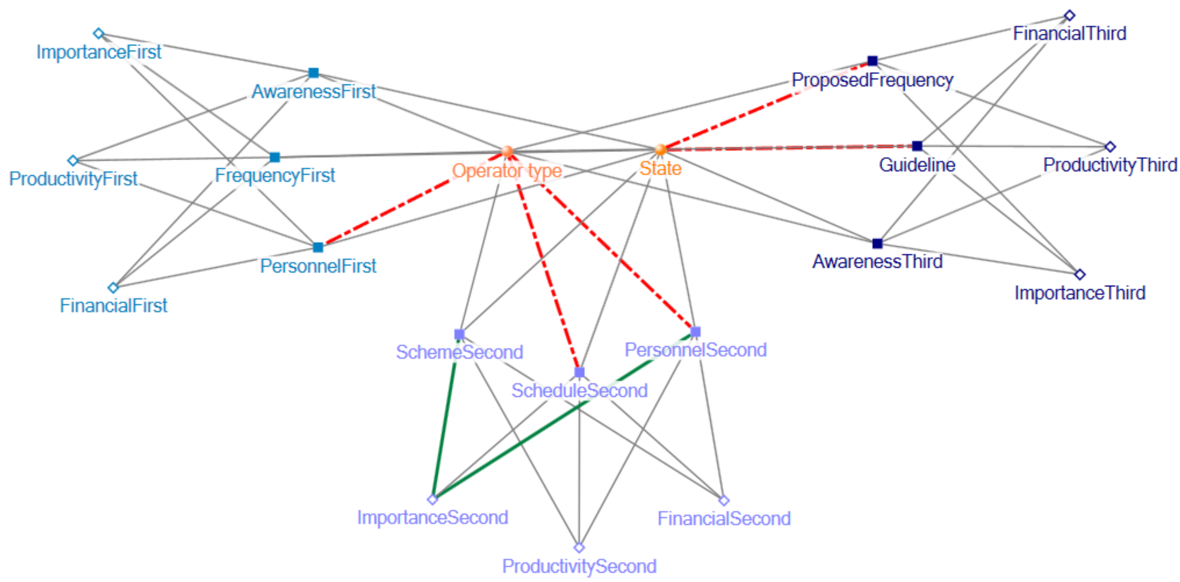

Figure 5.3 Interactions between operational characteristics (dots), inspection practices (squares) and perceptions (diamonds)

Note: 'First' represents pre-trip inspection; 'second' the time-distance based inspection and 'third' the mandatory independent inspection

5.4.4.2 Inspection practices and perceptions

The perceptions of productivity and financial impact did not seem to affect operators' practices of any inspection type while the perceived importance of time-distance based inspections was positively associated with the practices of this inspection type. Operators who conducted time-distance based inspections perceived it to be significantly more important (Median=5) than the "Otherwise (No and don't know)" group (Median=1) (Mann-Whitney U Test, U=53.500, p=.000), and those who used a combination of internal staff and outsourcing had the highest perceived importance (Median=5) while those who relied solely on outsourcing had the lowest (Median=4) (Kruskal-Wallis H test, χ^2 (2) = 8.842, p = 0.012)[1]. These associations are marked as green solid lines in Figure 5.3.

5.5 Discussion

Overall, the results demonstrated variations in the existence and implementation of bus inspections in the industry.

Pre-trip inspections were widely conducted, regardless of perceptions, and the practices were generally homogeneous among different types of operators. The high variability of the duration of the inspection and the field evidence that pre-trip inspections were not properly conducted, as identified on several occasions during random roadside inspections (Bus Safety Victoria, 2014) warrant more in-depth examination of procedures and personnel conducting this inspection (Gou et al., 1999).

Compared with pre-trip and mandatory, independent inspections, time-distance based inspections were less likely to be undertaken (especially in Victoria) and were perceived as being less important. The perceived importance was associated with the implementation and those who did not conduct this inspection type considered it to be not necessary and less important for their fleet. This is an interesting finding and it might be beneficial for safety regulators to communicate the importance of this inspection to bus operators using audits, bus forums, bus safety week campaigns, and newsletters to encourage proactive maintenance.

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[1] Personnel was regrouped into internal, outsource and combination here.

The practices of time-distance based inspections varied widely among the different types of operators. Small, rural operators were more likely to manually schedule and outsource time-distance based inspections. In contrast, metropolitan and non-metropolitan medium operators were more likely to use a computerized system for scheduling and undertake the servicing in-house. These differences may be associated with the fact that small, rural operators often have fewer resources for inspection and maintenance. Attempts have been made to overcome the challenges posed by limited resources and the key lies in the way in which maintenance is organized, managed, and performed (Etschmaier, 1985). According to some practitioners in the field, there have been agreements set up between selected operators in Victoria whereby the smaller ones contract their inspections to the large regional operators to overcome the constraint of their maintenance resources and benefit from economies of scale. A similar yet slightly different concept of Regional Maintenance Centres, where rural operators can share the maintenance resources (staff, facility, expertise) of their regional counterparts have been well established and these centers are already in operation in some states in the US (Beruvides, Simonton, Ng, Chaivichitmalakul, & Waters, 2008; Beruvides et al., 2009; Ng et al., 2012). Mandatory, independent inspections were well acknowledged; however, it was of concern that a substantial number of operators considered them to be a significant financial impost. The guidelines and proposed frequency varied across the jurisdictions due to the different safety regulations and regimes in each. The inclusion of operators in additional jurisdictions in the study would have been desirable, however, it was not possible at the time it was undertaken. A direction for further study is to benchmark mandatory, independent inspections, including guidelines, frequency, and financial impost, among jurisdictions to establish best practice.

5.6 Conclusion

This chapter aimed to evaluate the inspection practices of Australian bus operators. A study was conducted in three jurisdictions and investigated the characteristics, inspection practices, and perceptions of inspections by 171 bus operators. A series of statistical analyses were performed to assess industry practices and scrutinize the factors of influence.

The results showed that pre-trip inspections were widely conducted irrespective of the nature of the bus operation or the operator's perceptions of this inspection type. Time-distance based inspections were comparatively weakly implemented with the practices being diverse. Mandatory, independent inspections were also well-acknowledged, although the schemes varied across jurisdictions due to the specific regulations within each.

The identified issues included weaker recognition and implementation of time-distance based inspections and the non-comparable inspection practices of small, rural operators. The corresponding recommendations included more intensive promotions of time-distance based inspections and the advancement in sharing maintenance resources among operators, such as the establishment of Regional Maintenance Centres.

Implications for future research arising from this study include: that the procedures and personnel conducting pre-trip inspections be investigated and; mandatory, independent inspections across jurisdictions be benchmarked to identify industry best practice.

It is anticipated that these insights will provide safety regulators and researchers with opportunities to improve inspection practices.

Chapter 6 IDENTIFYING THE CONTRIBUTING FACTORS TO BUS INSPECTION OUTCOMES AND QUANTIFYING THEIR EFFECTS

6.1 Introduction

A comprehensive understanding of bus roadworthy condition was described in Chapter 4. To enhance bus roadworthiness, there is an additional need to understand the factors associated with poor roadworthy outcomes. This chapter aims to identify the contributing factors to bus inspection outcomes and quantify their effects.

The bulk of the work presented in this chapter has been summarised into a research paper: Qiu, Logan, Oxley, and Lowe (2019).

This chapter begins with a review of the literature addressing the factors influencing inspection outcomes, which are then interpreted in the context of the fleet setting. The hierarchical data structure is then illustrated, followed by the discussion of the derived challenges and the corresponding modeling approach. The results section presents the descriptive statistics and the findings from model estimations. The chapter concludes with a discussion of the implications of the findings for regulation practices and future research.

6.2 Research Context

6.2.1 Factors that influence vehicle inspection results

Previous studies have identified a range of factors that affect vehicle inspection outcomes (Cohen & Silkunas, 2018), with a particular focus on emission inspections (Beydoun & Guldmann, 2006; Bin, 2003; Peck et al., 2015; Washburn, Seet, & Mannering, 2001). From the perspective of vehicular characteristics, age, odometer reading, and vehicle make have received the most scrutiny. There is a general, intuitive, consensus that the probability of inspection failure increases as vehicles age and cover more distance (Bivona & Montemaggiore, 2010; Cohen & Silkunas, 2018; Mall, Center, & Sekera, 2016). In addition, vehicle make has been shown to be a strong determinant of the likelihood of passing an inspection, with some makes performing significantly better than others (Beydoun & Guldmann, 2006; Bin, 2003; Peck et al., 2015; Washburn et al., 2001). There are mixed results on the role that vehicle weight plays, in terms of both sign and significance (Beydoun & Guldmann, 2006; Peck et al., 2015). Other commonly examined vehicular factors include engine characteristics (e.g. size, number of engine cylinders) (Beydoun & Guldmann, 2006; Bin, 2003; Washburn et al., 2001) and fuel characteristics (e.g. type, injection, economy) (Beydoun & Guldmann, 2006; Bin, 2003; Peck et al., 2015; Washburn et al., 2001), most likely due to the emphasis on emission outcomes. Inspection results also appear to be influenced by vehicle maintenance regimes, including type (e.g. preventative vs corrective), frequency, and the facility carrying out maintenance (Jakimovska & Duboka, 2015). Washburn et al. (2001) recognized that vehicle maintenance might also alter the relationship between age and inspection outcomes. Existing literature on vehicle inspection outcomes, however, either only focuses on private passenger vehicles or does not differentiate between different vehicle ownership types (private vs commercial).

6.2.2 Risk factors in the context of fleet setting

As elaborated in Section 2.3.3, buses, unlike private vehicles, are commercial vehicles operated and maintained within a fleet setting, which leverages almost all of the above-discussed influential factors for vehicle inspection outcomes (Mitchell, Friswell, & Mooren, 2012). Fleet replacement decisions regarding when to replace old buses with new ones impact overall vehicle age and odometer readings (Feng & Figliozzi, 2012; Simms, Lamarre, Jardine, & Boudreau, 1984). Fleet procurement strategies determine vehicle characteristics including make, body, configuration, weight, engine characteristics, and fuel type (Loxton, Lin, & Teo, 2012; Stasko & Oliver Gao, 2010; Warmerdam, Newnam, Sheppard, Griffin, & Stevenson, 2017). Fleet operation planning including service schedule, vehicle assignment, and maintenance resource allocation shape the maintenance regime (Haghani & Shafahi, 2002).

Furthermore, the fleet setting introduces influential factors that are difficult to measure (as illustrated in Section 4.5.2.2) and fleet safety culture (Short, 2007) has been proven to have overarching impacts on inspection outcomes. Consequently, it is of critical importance to take the fleet setting into consideration in the examination of bus inspection outcomes.

6.3 Research Data

This research component examined the annual inspection (roadworthiness test) records of Victorian buses. As opposed to the individual indicators corresponding to each of the 14 bus components in Chapter 4, the interest of this research component was the overall bus inspection outcomes, recorded as pass versus fail. During the research period (2014-2018), there were 24,310 inspection records of 7,105 buses from 234 operators. Inspection level attributes included season, age, and odometer reading at inspection; vehicular characteristics included vehicle make, body and configuration; and operational characteristics included fleet size, location of operation, and service type (see Section 3.5 for details). Some records (n = 933) had missing or conflicting values in some of the attributes and were therefore excluded from further analysis. As a result, a total of 23,377 inspection records of 6,841 buses by 234 Victorian operators made up the final sample for analysis.

6.4 Methodology

6.4.1 Hierarchical Structure

As illustrated in Figure 6.1, the data exhibits a three-level hierarchical structure, with inspections nested within vehicles, which are nested within operators. Inspections of the same vehicle share common vehicular characteristics and are thus correlated. Similarly, buses from the same operator share common operational characteristics (e.g. maintained and prepared for annual inspections in a similar way) and are therefore correlated (StataCorp, 2013).

The hierarchical structure of the data poses a challenge, as observations for units belonging to the same cluster are not independent of one another, violating the traditional model assumption of residual independence (Abdul Manan, 2014; Imprialou, Quddus, & Pitfield, 2015; Jones & Jørgensen, 2003; Yoon, Kho, & Kim, 2017). Disregarding the dependence between observations within the same cluster is likely to cause statistical inaccuracies, including underestimation of standard errors, overstatement of statistical significance and excessive Type I errors (Adanu, Smith, Powell, & Jones, 2017; Bryk & Raudenbush, 1992; Dupont, Papadimitriou, Martensen, & Yannis, 2013; Familar, Greaves, & Ellison, 2011; Goldstein; Haghighi, Liu, Zhang, & Porter, 2018; Jones & Jørgensen, 2003; Kreft & de Leeuw, 1999; Peugh, 2010; Vanlaar, 2005), and therefore should be avoided. Multilevel modeling techniques are identified as the most appropriate approach to analyze these data (Haghighi et al., 2018).

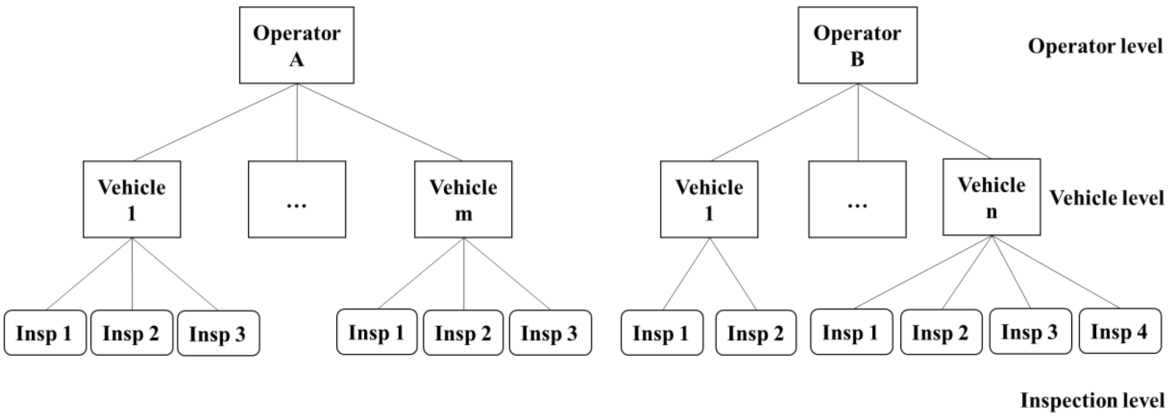

Figure 6.1 Hierarchical structure of Victorian bus inspection results

6.4.2 Multilevel Modeling

Multilevel modeling takes into consideration within-cluster correlations and captures the potential between-cluster heterogeneity due to unobserved factors. It has been used extensively to properly account for hierarchical structures in a variety of disciplines such as econometrics, education, psychology, and epidemiology (Adanu et al., 2017; Goldstein, Browne, & Rasbash, 2002; Peugh, 2010; Rabe-Hesketh & Skrondal, 2008; StataCorp, 2013) and has also achieved practical implications in several transport applications (Haghighi et al., 2018; Meesmann, Martensen, & Dupont, 2015). Jones and Jørgensen (2003) developed a multilevel binary logit model to assess the impact of occupant and vehicle characteristics on fatality risk on Norwegian public roads. Casualties were clustered within crashes and crashes were clustered within municipalities. The results revealed that there was a correlation among injury severity outcomes of casualties involved in the same crashes or crashes that occurred in the same municipalities. Abdel-Aty, Ekram, Huang, and Choi (2011) used a multilevel ordered logit model to investigate the impact of occupant characteristics, roadway features, and light condition on severity outcome of fog- or smoke-related crashes in Florida. To account for the hierarchical structure of data, crashes were nested within road segments. Results showed that a significant correlation existed among crashes that occurred on the same road segments. Furthermore, the technique breaks down the variance in the outcome variable and provides insight into the proportion of each level of the hierarchy in the outcome variance, which is not available from traditional methods (Familar et al., 2011; Jones & Jørgensen, 2003).

In transport safety studies where there has been great interest in examining the effects of various factors on crash outcome and infringement of explanatory variables at different levels, multilevel approaches have been appreciated as appropriately handling various hierarchical data structures. As presented in Table 6.1, the literature covers crash occurrence (with direct and surrogate crash measurements), severity and infringement, and examines both aggregate and disaggregate structured data (Dupont et al., 2013). Several consistent findings have been reported across the literature: improved model fit and the identification of a substantial proportion of variation in the outcome at the higher level by multilevel modeling, as opposed to traditional single-level modeling.

In the literature, the multilevel modeling approach is also known by a variety of names including mixed-effects models (Cloutier et al., 2017), hierarchical models (Yoon et al., 2017), random effects/random parameter/random coefficient models, random intercept/variance component models (Abdul Manan, 2014; Familar et al., 2011; Jones & Jørgensen, 2003), etc. The terms “multilevel model” and “mixed-effects model” will be used interchangeably hereinafter.

Table 6.1 Summary of studies on multilevel modeling in transport safety

Author	Location	Category	Dependent variable	Estimation model	Hierarchical structure	Aggregate /disaggregate[1]
Cloutier et al. (2017)	Quebec, Canada	Crash occurrence (surrogate)	Interactions between pedestrian and vehicles	Mixed-effect logistic	Two levels (Crossing sites, interaction)	Aggregate
Abdul Manan (2014)	Malaysia		Serious traffic conflicts	Mixed-effects logistic	Two levels (Traffic volume category, traffic conflict)	Aggregate
Jovanis, Aguero-Valverde, Wu, and Shankar (2011)	Virginia, US	Crash occurrence (direct)	Event (crash or near crash)	Multilevel logistic	Two levels (Driver, event)	Disaggregate
Kim, Lee, Washington, and Choi (2007)	Georgia, US		Crash	Multilevel logistic	Two levels (Intersection, crash)	Aggregate
Zhang, Khattak, Liu, and Clarke (2018)	US	Crash severity	Rail-pedestrian trespassing crash severity	Multilevel ordered logit	Two levels (County, crash)	Aggregate
Haghighi et al. (2018)	Illinois, US		Crash severity	Multilevel ordered logit	Two levels (Road segment, crash)	Aggregate
Adanu et al. (2017)	Alabama, US		Crash severity	Multilevel logistic	Two levels (Region, driver)	Aggregate

Yoon et al. (2017)	South Korea		Local bus crash severity	Multilevel ordered logit	Two levels (Region, crash)	Aggregate
Chen et al. (2016)	New Mexico, US		Crash severity	Hierarchical logistic	Two levels (Crash, vehicle/driver)	Disaggregate
Quddus (2015)	England, UK		Crash severity	Multilevel ordered logit	Three levels (Area, crash, driver)	Aggregate
Lenguerrand, Martin, and Laumon (2006)	France		Crash severity	Multilevel logistic	Three/two (Crash, (vehicle), occupant)	Disaggregate
Jones and Jørgensen (2003)	Norway		Crash severity	Multilevel logistic	Three levels (Municipality, crash, individual)	Aggregate
Meesmann et al. (2015)	EU	Infringement	Driving under the influence of alcohol	Multilevel logistic	Two levels (Nation, individual)	Aggregate
Familar et al. (2011)	Sydney, Australia		Speeding	Multilevel logistic	Four levels (Individual, day, trip, segment)	Aggregate

[1]The highest level of the hierarchical structures

6.4.3 Model Expression

In this study, a three-level logistic regression model (as shown in Equation (6.1)) was formulated to examine the effects of characteristics attributable to inspections, vehicles, and operators on bus inspection outcomes, taking into the within-operator and within-vehicle correlations consideration. The outcome of inspection *i* for vehicle *j* run by operator *k*, denoted as y_{ijk}, is a binary variable with y_{ijk} = 0 indicating 'pass' and y_{ijk} = 1 representing 'fail'. The binary outcome of the dependent variable makes logistic regression an appropriate analysis technique (Beydoun & Guldmann, 2006; Peck et al., 2015).

$$logit(p_{ijk}) = log[\frac{p_{ijk}}{1-p_{ijk}}] = \beta_0 + \sum_{m=1}^{M} \beta_m X_{ijk} + \sum_{n=1}^{N} \delta_n W_{jk} + \sum_{q=1}^{Q} \gamma_q Z_k + u_k + v_{jk} + e_{ijk}$$

(6.1)

Where

i, j, k = indexes of first level (inspection), second level (vehicle), and third level (operator), respectively. In this case, the subscript *k* takes the value from 1 to 234 (the number of operators), the subscript *j* takes the value from 1 to the number of vehicles in operator *k*, and the subscript *i* takes the value from 1 to the number of inspections for vehicle *jk*. Terms with subscript *k* vary across operators but are constant within an operator. Similarly, terms with subscript *jk* vary from vehicle to vehicle but are constant for a vehicle.

p_{ijk}= Pr (y_{ijk}= 1) = the probability that inspection *ijk* fails;

β_0= constant;

X_{ijk}, W_{jk}, Z_k= explanatory variables for first level, second level, and third level, respectively;

β_m, δ_n, γ_q= corresponding coefficients for first level, second level, and third level, respectively;

u_k = operator-level random intercept, $u_k \sim N(0, \sigma_u^2)$;

v_{jk}= vehicle-level random-intercept, v_{jk}~N (0, σ_v^2);

e_{ijk}= inspection-level residuals, e_{ijk}~N (0, σ_e^2);

It is assumed that being at different levels, these random quantities are independent.

The model is a random intercept model, which is widely used in multilevel modeling (Familar et al., 2011; Jovanis et al., 2011; Yoon et al., 2017) and enables the investigation of the variance proportion of variation at different levels, thus also knows as the variance component model. According to Equation (6.1), the variation in bus inspection outcome is decomposed into three levels: inspection variation (σ_e^2), vehicle variation (σ_v^2) and operator variation (σ_u^2). To evaluate the proportion of total variance in the outcome that is associated with each of the three levels, the intra-class correlation coefficient (ICC) needs to be computed. When calculating ICC, the first level residual is commonly assumed as logistic distributed with a variance of $\pi^2/3$ (Adanu et al., 2017; Dupont et al., 2013). Therefore, for the three-level model in this study, the ICCs can be calculated as shown below.

$$\text{ICC Level 2,}\ \ \rho_2 = \frac{\sigma_v^2}{\sigma_u^2+\sigma_v^2+\pi^2/3} \tag{6.2}$$

ρ_2: the proportion of total variance in the outcome explained by between-vehicle variance.

$$\text{ICC Level 3,}\ \ \rho_3 = \frac{\sigma_u^2}{\sigma_u^2+\sigma_v^2+\pi^2/3} \tag{6.3}$$

ρ_3: the proportion of total variance in the outcome explained by between-operator variance.

6.4.4 Model Evaluation

It is worth noting that, due to the nature of the data, the number of inspections per vehicle was small (usually around four inspections per vehicle). Furthermore, nearly half of the operators (45.3%) had no more than five buses. Caution, therefore, needs to be exercised when applying multilevel modeling to disaggregate data where the numbers of observations within the clusters are low. It is suggested that the application of multilevel modeling be assessed in the following aspects: model fit, identification and explanation of random variation at specific levels of the hierarchy, and correct estimation of the significance of the parameters (Dupont et al., 2013). A single-level logistic model was estimated as a reference for model performance comparisons, with Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC) used to assess model performance, where smaller AIC and BIC values indicate better model fit (Abdul Manan, 2014; Cloutier et al., 2017). All analyses were performed in Stata 15.

6.5 Results

This section presents the descriptive statistics and the estimation results for the three-level and single-level logistic models.

6.5.1 Descriptive Statistics

According to Table 6.2, the average bus age at inspection was 10.4 years old. Scania, Mercedes Benz, and Volvo were the most popular makes in the overall Victorian bus fleet and comprised more than three-fifths of the fleet. The majority (72.6%) of vehicle bodies were built by domestic body builders. Although large operators were small in number (13.7%), they operated nearly three quarters (72.0%) of Victorian buses. In contrast, over 70 percent of operators (71.8%) were small, with about 13.9 percent of Victorian buses under their control.

Operator depot location was mapped as shown in Figure 6.2 and Figure 6.3. The size of the dots is proportional to operator fleet size. Metropolitan areas are characterized by large operators, while the regional areas are mainly served by sparsely distributed small to medium operators. The colour of the dots is associated with operator type (Figure 6.2), service type (Figure 6.3) of the operators.

Table 6.2 Descriptive statistics

Levels	Variables		Frequenc	Percentage/Mean
Inspection level: N=23,377 inspections	**Inspection result**			
	Pass		19,229	82.3
	Fail		4,148	17.7
	Season			
	Summer		5,796	24.8
	Autumn		6,363	27.2
	Winter		5,647	24.2
	Spring		5,571	23.8
	Age (years)		-	10.4
	Odometer reading ('000)		-	404.8
Vehicle level: N=6,841 buses	**Make**			
	Scania		1,603	23.4
	Mercedes Benz		1,363	19.9
	Volvo		1,333	19.5
	MAN		529	7.7
	Iveco		277	4.1
	Higer/King Long/Yutong/BCI[1]		233	3.4
	Toyota		462	6.8
	Mitsubishi		446	6.5
	Hino		378	5.5
	Others		217	3.2
	Body			
	Volgren (Australian)		2,254	33.0
	Other Australian body builders		2,713	39.7
	Higer/King Long/Yutong/BCI[2]		560	8.2
	Arakawa		462	6.8
	Mitsubishi		445	6.5
	Others		407	6.0
	Configuration			
	Bus		3,497	51.1
	Coach		3,344	48.9
Operator level: N=234 operators. Number of operators (number of buses)	**Size vs location**			
	Large	Metropolitan	15 (3,533)	6.4 (51.6)
		Regional	17 (1,394)	7.3 (20.4)
	Medium	Metropolitan	16 (464)	6.8 (6.8)
		Regional	18 (498)	7.7 (7.3)
	Small	Metropolitan	28 (269)	12.0 (3.9)
		Regional	140 (683)	59.8 (10.0)
	Service type			
	Route		54 (4,626)	23.1 (67.6)
	Charter & Tour		113	48.3 (29.0)
	School & Other		67 (232)	28.6 (3.4)

[1] These makes were merged because of their low frequency and shared similarities.
[2] These models were merged for the same reason as stated above.

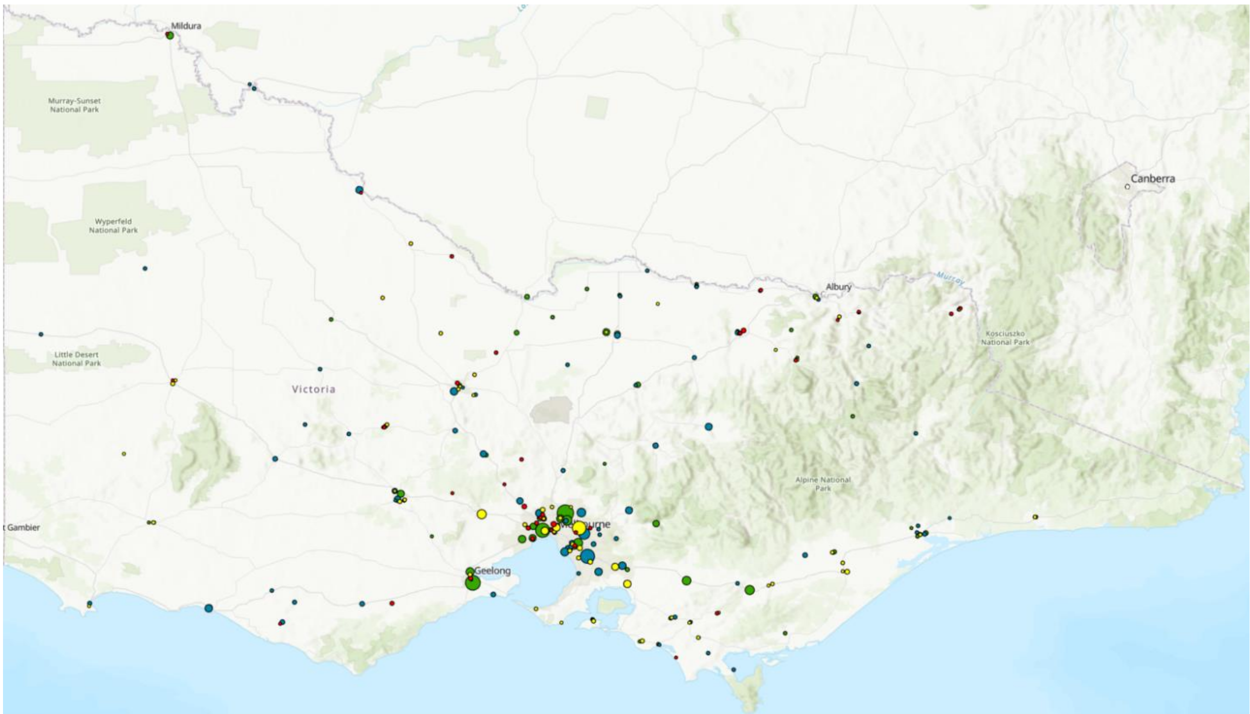

Figure 6.2 The geographical distribution of the 234 bus operators by operator type

Note: Green represents the Type 1 operator, blue Type 2, yellow Type 3 and red Type 4

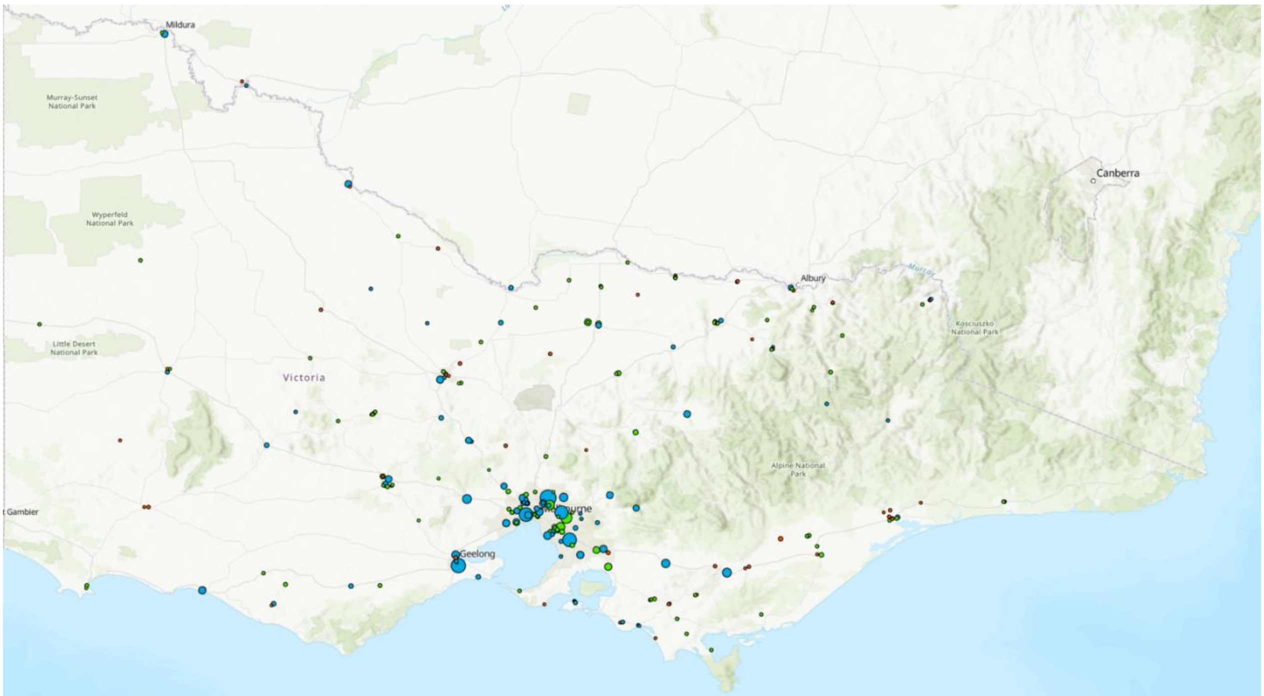

Figure 6.3 The geographical distribution of the 234 bus operators by service type

Note: Blue represents Route operator, green Charter & Tour, and orange School.

6.5.2 Model Results

The three-level model specified in Equation (6.1) and the single-level model were estimated and the results are summarised in Table 6.3. Only variables with at least one significant sub-category in at least one of the models are presented. Vehicle body was highly predictable by vehicle make and was therefore omitted in the final model (refer to Appendix C: Table 6.5 for further details). The multilevel logistic model performed considerably better than the single-level model according to the AIC and BIC criteria (Hilbe, 2011). In addition, the standard errors in the single-level model were underestimated, consistent with previous literature (Goulias & Kim, 2001; Jovanis et al., 2011; Vanlaar, 2005).

There was a trend of increasing odds of inspection failure with both increasing vehicle age and odometer reading, which was in the expected direction and consistent with previous literature (Peck et al., 2015). Every yearly increase in age resulted in an 8.0 percent increase in the odds of inspection failure and every increase of 100,000 kilometres in odometer reading led to an 8.1 percent increase in the odds of inspection failure.

Among large, heavy buses, the risk of failing an annual inspection was lowest for Volvo, followed by Scania (OR = 1.508, p = 0.000) and Mercedes Benz (OR = 1.700, p = 0.000). MAN and Iveco vehicles showed positive odds ratios between 2 and 3, while the highest inspection failure risk was observed for Higer/King Long/BCI/Yutong buses (OR = 4.789, p = 0.000). Examining the performance of medium-sized buses, the odds of failing the annual inspection for Hino buses was 1.16 times that of Toyota vehicles (although statistically insignificant), with Mitsubishi 1.34 times (p = 0.014). Regarding vehicle configuration, coaches carried an elevated risk of failing an inspection (OR = 1.203, p = 0.001).

With regard to operator size, the lowest inspection failure risk was observed among large operators, irrespective of depot location. Concerning location, there were no significant differences between metropolitan and regional operators for large (OR = 1.266, p = 0.586) and medium (OR = 0.805, p = 0.616) ones, whilst small operators in metropolitan areas performed significantly worse than their counterparts in regional areas (OR = 2.449, p = 0.002).

Table 6.3 Modeling results

		Multilevel logistic model		Single-level logistic model	
Fixed effects		Odds ratio	SE	Odds ratio	SE
Age		1.080***	.0043	1.058***	.0034
Odometer reading (‘000)		1.0008***	.0001	1.0008***	.0001
Vehicle make					
Large heavy makes					
Volvo (ref.)					
Scania		1.508***	.1195	1.635***	. 1079
Mercedes Benz		1.700***	.1348	1.695***	.1083
MAN		2.350***	.2246	2.855***	.2194
Iveco		2.891***	.3352	2.452***	.2366
Higer/King Long/Yutong/BCI		4.789***	.6169	5.045***	.5147
Medium-sized makes					
Toyota		1.650***	.1772	1.829***	.1581
Hino		1.918***	.2173	1.774***	.1630
Mitsubishi		2.212***	.2279	2.611***	.2195
Other		1.442*	.2149	1.204	.1467
Configuration					
Bus (ref.)					
Coach		1.203**	.0689	1.141**	.0498
Size	**Operator location**				
Large	Metropolitan (ref.)				
	Regional	1.266	.5486	1.411***	.0784
Medium	Metropolitan	2.849*	1.2648	3.226***	.2098
	Regional	2.294	.9885	2.328***	.1595
Small	Metropolitan	4.668***	1.9723	3.695***	.3208
	Regional	1.906	.6690	1.975***	.1258
Intercept		.015***	.0050	.024***	.0018
Random effect parameters					
Level 2 (Vehicle level)					
Intercept variance σ_v^2		.223***	.0518	-	-
Level 3 (Operator level)					
Intercept variance σ_u^2		1.440***	.1895	-	-
Observations		(23,377, 6,841, 234)		23,377	
AIC		18,130.90		19,718.91	
BIC		18,300.15		19,872.04	

*p<0.05, **p<0.01, ***p<0.001.

The random effects are summarized in the lower part of Table 6.3. There were statistically significant variations in inspection outcomes across vehicles and operators after controlling for the variables in the fixed part of the model, verifying the presence of the hierarchical structure. The ICC indices (Equations (6.2) and (6.3)) suggest that 29.1 percent of the variation in inspection results occurred across operators and 4.5 percent at the vehicle level, indicating that unmeasured operator characteristics were an important influence, in addition to a relatively small vehicular effect.

An additional key goal of this research component was to determine the level of inspection failure risk associated with different operators, holding constant the effects of the explanatory variables within the model. For this purpose, the random intercept value for each operator (u_k) was estimated. Figure 6.4 shows the estimated intercepts for different operators ranked in order of magnitude, with the size of the dots being proportional to the fleet size of the operator. The red line (along the X-axis) represents the population average, with those below the reference line performing better than average and those above worse than average. It is clear that there were two sub-populations at the extremes that were associated with a particularly high or low level of inspection failure risk.

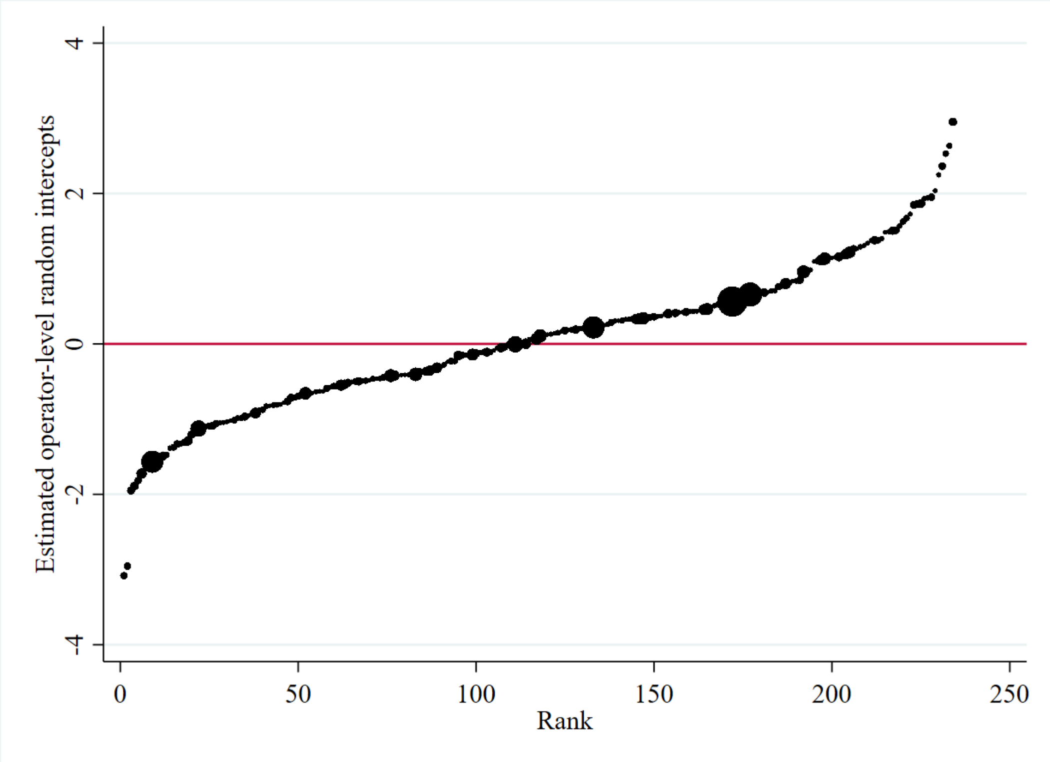

Figure 6.4 Ranked estimated intercepts for different operators

Leaving all the explanatory variables behind, the technique was used to rank operators in such a way that the derived results could be compared with the operator classification where operators were classified into four types based on their composition of inspection failure patterns (Section 4.5.2.1). As shown in Table 6.4, the majority (88.7%) of Type 1 & Type 2 operators (with around 95% and 85% of the inspections being non-failure, respectively) were ranked as above average, and the vast majority (98.2%) of Type 3 & Type 4 operators (with approximately 30% and 70% of the inspections being a failure, respectively) were ranked as below average, demonstrating a high level of consistency and negligible discrepancy. Figure 6.5 further illustrates the correspondence between the outcomes from operator ranking and classification, with the four operator types marked in respective colours. The cross validation of the two outcomes facilitated the interpretation of operator types. Type 1 was deemed as the best performing class and Type 4 the worst in Chapter 4. Types 2 & 3, in general, fell between these two extremes, with Type 2 the better performing class and Type 3 the worse performing.

Table 6.4 Cross-validation between operation classification and ranking

	Type 1	Type 2	Type 3	Type 4	Total
Above average	57	53	2	0	112
Below average	0	14	71	37	122
Total	57	67	73	37	234

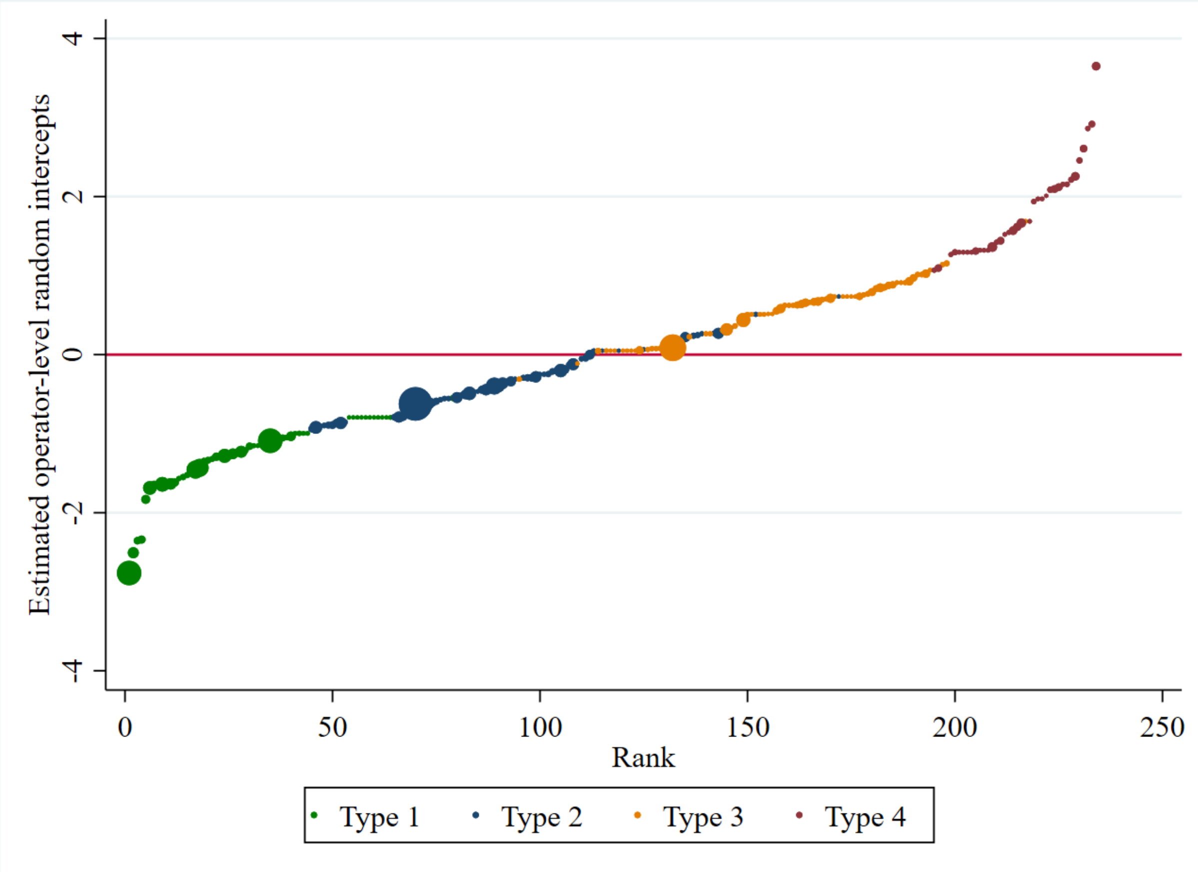

Figure 6.5 Correspondence between the outcomes from operation ranking and classification

6.6 Discussion

6.6.1 Implications for regulation practice

The findings from this study serve as a foundation for bus safety regulators to formulate evidence-based policies aimed at enhancing bus roadworthiness. For example, more stringent maintenance requirements for buses beyond a certain age or odometer reading could be set based on the findings of this study.

It is encouraging that the three most popular makes of buses operating in Victoria, which accounted for over 60 percent of the Victorian bus fleet (in number), were the best performing. The insights into the inspection failure risk by vehicle make could be used to guide the procurement strategies by fleet managers. Fleet managers should be encouraged to carefully evaluate vehicle acquisition alternatives by not only comparing purchasing costs but also maintenance costs.

Regarding the finding that coaches (predominantly used for tour and charter services) carried an elevated risk of inspection failure compared with buses (used to provide other services, e.g. route and school services), it is important to note that coaches and buses are built under different standards (e.g. superstructure, floor height, seating arrangements) to accommodate service type. Given their different operating characteristics, it is highly likely that these vehicle configurations are subject to different wear patterns. In addition, tour and charters operators, unlike route and school ones, are not contracted or subsidized by the government. They are not subject to the stringent requirements specified in government contracts and may struggle more with financial pressure, both of which may result in compromised preventative maintenance. The maintenance regime in Victoria does not differentiate the requirements for bus and coach. Quebec, Canada, on the other hand, requires coaches to undergo a mandatory mechanical inspection every 30 days or every 12,000 km (whichever occurs first), in addition to the common biannual mandatory inspection for bus and coach (Quebec Automobile Insurance Corporation, 2019). The discrepancy identified between buses and coaches offered unique insights to the literature. It is recommended that further research be conducted to investigate the potential benefits and disadvantages of more frequent mandatory, independent inspections for coaches.

6.6.2 Limitations and Implications for Future Study

Multilevel modeling accounted for and quantified the unobserved heterogeneity, providing significant advances over traditional techniques. Still, it could not compensate for the absence of a number of potentially important variables. Both anecdotal and research evidence suggested that road class/surface conditions (e.g. sealed vs unsealed) (Anderson & Davenport, 2005) and operating mode (e.g. buses that spend long hours stationary or travelling at very low speeds vs buses that spend short hours travelling at high speeds) make a difference to inspection outcomes. Odometer readings, however, provide no indications regarding where or how the travelled distances are made. Current GPS tracking technology enables the collection of real-time position data, which can be used to estimate vehicle kilometres travelled by road class and mode. The inclusion of such data in future studies would provide far more detailed data on speed distributions and operating environments.

The substantial proportion of variance at the operator level emphasized the need for an in-depth study, as proposed in Section 4.5.2.2. It is recommended that future research focus on a selection of individual operators to capture some of the less tangible factors that influence roadworthy performance such as maintenance management systems (Bus Safety Victoria, 2017b) and safety culture (Short, 2007).

6.7 Conclusion

This research component aimed to identify the factors contributing to inspection outcomes and separately quantified the effects attributable to inspections, vehicles, and operators. The analysis was based on annual bus inspection data in Victoria, Australia between 2014 and 2018, consisting of 23,377 inspections of 6,841 vehicles run by 234 operators. A unique aspect of this study is the realization of the hierarchical data structure where inspections are nested within vehicles and vehicles within operators. The subsequent application of the three-level logistic model offered greater consistency and outperformed the single-level model with regard to model fit, estimation accuracy, and identification of the random variation in inspection outcomes at specific levels of the hierarchy.

The results offered insights into the effects on bus roadworthiness of characteristics attributable to inspections, vehicles, and operators. Increasing vehicle age and odometer reading were positively associated with increased inspection failure risk. Vehicle make played an important role in inspection outcomes, with the performance of different makes varying significantly. Vehicle configuration also mattered, with coaches having a higher odd of failing an inspection than the bus. Regarding operator size, the lowest inspection failure risk was found among large operators, regardless of the location of operation. In contrast to the majority of previously published studies in the literature (Section 6.2.1), which mainly focused on vehicular characteristics, this analysis incorporated operator level characteristics and clearly demonstrated their importance for inspection outcomes. The multilevel analysis revealed that 29.1 percent of the variation in inspection outcomes occurred across operators and 4.5 percent across vehicles. The substantial portion of the total variance in inspection outcomes at both the vehicle and operator levels could not be quantitatively explained in a non-hierarchical model. The level of inspection failure risk associated with the individual operator was also presented, both controlling for and relaxing the fixed effects in the model, and the latter cross validated the results in Chapter 4.

Some policy implications for safety regulators included: more stringent maintenance requirements for older buses and those with high odometer readings; information to assist with assessing vehicle total cost of ownership; and the provision of the groundwork for the selective targeting of operators.

Several future research topics are warranted to enhance the understanding of bus roadworthiness, including scrutinizing the potential benefits of more frequent mandatory inspections for coaches, the capture of more variables, and the conduct of in-depth operator studies to understand the heterogeneity.

Chapter 7 EXPLORING THE IMPACTS OF OPERATIONAL CHARACTERISTICS ON FLEET INCIDENT OUTCOMES

7.1 Introduction

The findings from Chapter 4-6 have so far emphasized the impacts operators had on bus inspection practices and inspection outcomes. This chapter sets out to extend the understanding of the impacts of operational characteristics on fleet safety outcomes, taking fleet roadworthy performance into consideration.

As discussed in Section 2.3.2, much of the previous research addressing bus safety has mainly focused on the region (e.g. state), route, road segment, or individual (incident/driver/vehicle) level, rarely giving any thought to the fleet setting of bus operation. Research has shown that the characteristics of the commercial operator influence their safety performance, with the focus fixed on freight carriers (Cantor, Osborn, & Singh, 2014; Chang & Yeh, 2005; Davey, Wishart, Freeman, & Watson, 2007; Mitchell et al., 2012; Qiu et al., 2019). Given the differences between passenger and freight carriers, the knowledge in freight cannot be directly transferred to passenger carriers, leaving a gap in the literature with regard to the safety performance of bus operators of varying characteristics. This research component centred on exploring the effects of operational characteristics on bus incident occurrence at the operator level.

Much of the work presented in this chapter originated in our published research paper: Qiu, Logan, Oxley, and Lowe (2020).

This chapter starts with an inspection and description of the data structure. The derived challenge of the data is then illustrated, as well as the discussion and formulation of corresponding modeling approaches. This is followed by the estimation and comparison of the alternative models. The finalized results are then discussed in depth. It concludes with a discussion on the implications of findings for bus safety research and regulators.

7.2 Research Data

7.2.1 Incident Dataset

As described in Section 3.5, this research component utilized the bus incident dataset managed by Transport Safety Victoria. During the study period (1/07/2014-30/06/2018), a total of 971 incidents were recorded. Of these, records that involved intentional acts from a third party (e.g. objects thrown at bus, assault, arson) or had missing information (e.g. missing operator identity) were excluded. As a result, a total of 691 incidents were included for analysis.

7.2.2 Disaggregate vs Aggregate

In terms of the number of incidents one entity has, the selection of temporal scales (aggregate vs disaggregate) has an impact on incident frequency as well as the representation of explanatory variables. Smaller time intervals (disaggregate) allow the consideration of potential time variation in explanatory variables (fleet, traffic, and other relevant attributes) while tend to generate excess zeros (Lord, Washington, & Ivan, 2005), which is discussed in depth in the next section. The opposite stands true for aggregate data.

7.2.3 Operator Inventory Data

The operational characteristics that were of interest to this study included fleet age, fleet size, fleet travel distance, operating environment, service type, and fleet roadworthy performance. The representation of some of the characteristics differed from the previous chapters due to the change in the type of the dependent variable (count vs categorical), the desire to reflect time variance in the variables.

Fleet size was represented by the number of buses as opposed to the categorical variable (small, medium, and large in Chapters 4 and 6) to better reflect changes over time. There was a particular interest in whether having a fleet older than 12 years had an impact on incident occurrence. It is the recommendation from Bus Industry Confederation (2017) and the regulation of Sydney bus contracts (Transport for NSW, 2017) that the average fleet age does not exceed 12 years at any time during the term. The primary traffic environment in which a bus operator operated was represented by ARIA+, a geographical index defining accessibility and remoteness, based on which Remoteness Area (Metropolitan vs Regional in Chapter 4) was categorized (Hugo Centre for Migration and Population Research, 2018). The values range from 0 to 15, with higher values representing higher remoteness. Fleet roadworthy performance was represented by synthesizing the risk and pattern of inspection failures during annual bus inspections estimated in Chapters 4 and 6 and operators were classified into two categories based on the agreement between risk and pattern classification, above vs below average.

7.2.4 Descriptive Statistics

Table 7.1 presents incident frequency and the explanatory variables in both aggregate and disaggregate terms. Some operators had missing, conflicting, or extreme values in some of the attributes and were then excluded from further analyses. As a result, a total of 226 operators were retained.

The data were first aggregated on a yearly basis, which is a common practice in the literature (Goh, Currie, Sarvi, & Logan, 2014b; Ma, Zhang, Chien, Wang, & Dong, 2017; Naznin, Currie, Logan, & Sarvi, 2016) and was referred to as the disaggregate setting in the context of this research component. Regarding the number of bus incidents operator i had in round t (Y_{it}), within the study period, the eligible operators produced 891[1] operator-round observations. Within each round, between 16 and 25 percent of the operators reported incidents, and a total of 79.9 percent of observations by operator-round were zeros.

In terms of the number of bus incidents operator i had in four years Y_i (aggregate), about 40 percent (41.6%) of the operators had incidents reported, and the number of recorded incidents ranged from 1 to 145.

Regarding the explanatory variables, the operating environment (ARIA+), service type, and fleet roadworthy performance did not change over time. Fleet size and fleet age were presented in both disaggregate and aggregate terms. Fleet travel distance was calculated based on the difference between odometer readings

[1] 891=213 × 4 +13×3: some operators exited the market earlier while others entered late.

recorded at the time of inspection and was not available on a yearly basis. As a result, the average value over the study period was used. According to the Australian Bureau of Statistics (2019), between 1 Jul 2017 and 30 Jun 2018, buses in Victoria had an average annual travel distance of 27.1-29.8 thousand kilometres, which verified the practice of using the average, the accuracy of the data and the representativeness of the operators in the dataset.

Table 7.1 Descriptive statistics of incident frequency and operational characteristics

Variable	Min	Max	Mean	SD
Operator (ID=1-226)	1	226	-	-
Round (2014-2015 as Round 1)	1	4	-	-
Incident				
Incident frequency (operator, four years)	0	145	3.03	13.23
Incident frequency (operator/round)	0	46	0.77	3.63
Operational characteristics				
Fleet average travel distance (1,000 km)	7.3	186.2	29.70	19.71
Aggregate				
Fleet size	1	823	26.45	76.61
Fleet age over 12	0	1	0.38	0.49
Disaggregate (Round specific)				
Fleet size	1	847	26.32	75.55
Fleet age over 12	0	1	0.39	0.49
Time constant				
ARIA+	0	6.3	1.58	1.45
Roadworthy performance	0	1	0.51	0.50
Service type	Frequency		Percentage (%)	
Route	52		23.0	
Charter and tour	110		48.7	
School & Other	64		28.3	

In view of the sparse number of incidents in the disaggregate setting and the inability to demonstrate the absence of the time-variance in the explanatory variables, this approach was discarded and the aggregate one adopted. Operator inventory data were then merged with incident data to facilitate the examination of the incident frequency with respect to operational characteristics.

7.3 Methods

This section started with the standard model structure for count data outcomes. The challenge of excess zeros was then illustrated, in parallel with which, corresponding modeling approaches were progressively formulated. In correspondence to the model formulation procedure, six models were then estimated, and a comparison exercise was undertaken to identify the superior model.

7.3.1 Model Formulation

7.3.1.1 Standard Count Model

Among the wide range of count models developed over the past decades, negative binomial (NB) modeling approach has been extensively used in road safety research given its ability to handle crash data that is discrete, random, nonnegative and typically over-dispersed (Cai, Lee, Eluru, & Abdel-Aty, 2016; Chin & Quddus, 2003; Hosseinpour, Yahaya, & Sadullah, 2014; Hou, Meng, Leng, & Yu, 2018; Kelvin Chun Keong, 2017; Lord & Mannering, 2010; Monaco & Redmon, 2012; Naznin et al., 2016).

For a NB model, the probability of operator i having Y_i incidents is given by:

$$P(Y_i) = \frac{\Gamma(Y_i+\frac{1}{\alpha})}{\Gamma(\frac{1}{\alpha})Y_i!}\left(\frac{\alpha\lambda_i}{1+\alpha\lambda_i}\right)^{Y_i}\left(\frac{1}{1+\alpha\lambda_i}\right)^{\frac{1}{\alpha}} \quad (7.1)$$

$\Gamma(.)$: a gamma function,

i: operator ID,

α: dispersion parameter,

and λ_i is the expected number of incidents for operator i.

7.3.1.2 Excess Zero

Approximately 60 percent of the incident frequency Y_i in the study period were zero, posing the methodological challenge of excess zeros where the allocated probability of observing zero by classic models (Poisson and NB) is insufficient to account for the zeros, leading to biased and inconsistent parameter estimates (Cai et al., 2016).

Zero-inflated (ZI) and hurdle models are the two foremost zero-altered models to deal with the issue of excessive zero counts and have been widely adopted in the literature (Atkins, Baldwin, Zheng, Gallop, & Neighbors, 2013; Hilbe, 2011; Hu, Pavlicova, & Nunes, 2011; Min & Agresti, 2005). The appropriate approach for analysis depends on the actual dataset under consideration. Therefore, it is essential and conventional to examine both before landing on the more appropriate approach (Cai et al., 2016; Hosseinpour et al., 2014; Raihan, Alluri, Wu, & Gan, 2019).

Zero-Inflated Model

The zero-inflated approach assumes that crash counts with excess zeros come from two states: an incident-free (zero-count) state, and an incident-prone (normal count) state (Lord et al., 2005; Shankar, Milton, & Mannering, 1997). In theory, no crashes will ever be observed in the incident-free state, and such entities are considered inherently safe (Shankar et al., 1997). Zeros generated under this process are addressed as 'structural zeros'. In the incident-prone (normal count) state, the crash frequencies follow some known distribution (e.g. Poisson or NB distribution). These distributions assume that some zero observations happen by chance (where the entities are unsafe but happen to have zero crashes observed during the period of observation) and allocate a probability to observe zero counts. These zeros are referred to as 'sampling zeros'. The probability density function of zero-inflated negative binomial (ZINB) model is given in Equation (7.2), which caters to zeros generated by the two different processes: (1) the process that generates structural zeros (zero-count state), and (2) the process that generates sampling zeros from a NB distribution (Cai et al., 2016; Hosseinpour et al., 2014; Hu et al., 2011; King & Song, 2018).

$$P(Y_i) = \begin{cases} p_i + (1 - p_i)(\frac{1}{1+\alpha\lambda_i})^{\frac{1}{\alpha}} & Y_i = 0 \\ (1 - p_i)\frac{\Gamma(Y_i+\frac{1}{\alpha})}{\Gamma(\frac{1}{\alpha})Y_i!}\frac{(\alpha\lambda_i)^{Y_i}}{(1+\alpha\lambda_i)^{Y_i+\frac{1}{\alpha}}} & Y_i > 0 \end{cases} \tag{7.2}$$

p_i: the probability of entity *i* being a zero-count state

Hurdle Model

The hurdle model approach (Cragg, 1971) represents an alternative way to handle data characterized by excess zeros (Cai et al., 2016; Hosseinpour et al., 2014). Unlike ZI models, the hurdle models assume that zeros in the count data are sampling zeros. That is, the entities with no incidents are safe over the study period only, not for the lifetime (not inherently safe) (Hosseinpour et al., 2014; Neelon, Chang, Ling, & Hastings, 2014; Zhen, Shao, & Zhang, 2018). The probability density function of the hurdle negative binomial (HNB) model is given in Equation (7.3), which is also partitioned into two parts. The first part is a binary model dealing with whether there are any incidents (positive counts (1) versus zero counts (0)), and the second part is a truncated-at-zero count model which generates only positive counts, given that incidents have occurred.

$$P(Y_i) = \begin{cases} p_i & Y_i = 0 \\ (1 - p_i)(1 - \frac{1}{(1+\alpha\lambda_i)^{\frac{1}{\alpha}}})\frac{\Gamma(Y_i+\frac{1}{\alpha})}{\Gamma(\frac{1}{\alpha})Y_i!}\frac{(\alpha\lambda_i)^{Y_i}}{(1+\alpha\lambda_i)^{Y_i+\frac{1}{\alpha}}} & Y_i > 0 \end{cases} \tag{7.3}$$

p_i: the probability of entity *i* being zero

The structure of the binary (logistic) part used in is given as follows:

$$logit\ (p_i) = ln(\frac{p_i}{1-p_i}) = Z_i\gamma + \xi_i \tag{7.4}$$

Z_i: a vector of explanatory variables for the logistic model,

and ξ_i is the residual error term for operator *i*.

The structure of the count part is given as follows:

$$ln(\lambda_i) = X_i\beta + \varepsilon_i \quad (7.5)$$

X_i: a vector of explanatory variables for the count model,

and ε_i is the residual error term for operator i.

Note that different predictors could be used in the two parts (Fang, Wagner, Harris, & Fillon, 2016; Zhen et al., 2018).

7.3.2 Model Estimation and Evaluation

7.3.2.1 Variable Selection Procedure

A forward selection procedure was used to incorporate variables of interest in the model. The basic model was set up considering the intercept and the exposure (fleet size/fleet travel distance) only. All other variables were added to the model on a one-by-one basis. A variable was kept in the model only if it was significant at the 0.1 level, and the goodness of fit of the model was improved by its inclusion.

7.3.2.2 Model Selection

There are some reservations regarding the use of the zero-inflated model for crash analysis (Lord, Washington, & Ivan, 2007; Lord et al., 2005; Son, Kweon, & Park, 2011). Zero-inflated models assumed the existence of the incident-free (inherently safe) state. However, as noted by Hauer (1999), a highway should not be claimed as inherently safe because a crash could occur in any place as long as there is vehicular traffic. Similarly, an operator should not be claimed as inherently safe as long as buses are running. It can be problematic to apply zero-inflated models to data not characterized by the two types of zeros assumed in the zero-inflated models. Hurdle models, on the other hand, assume that the zero observations are sampling zeros, acknowledging operators' potential to have incidents, which provides a better approximation to the nature of excess zeros in this study.

In addition to the fact that ZI models do not appeal to the nature of excess zeros in traffic safety research, the model may have convergence or local maxima problems due to their computation complexity (Son et al., 2011), leading to potentially unstable estimation of the parameters (Xu, Paterson, Turpin, & Xu, 2015). When applied to the current data, the ZI model estimation either failed to converge or had an inferior fit while hurdle models provided stable parameter estimations. ZI models were therefore excluded from further consideration.

Table 7.2 Model comparison

Models	df	log-likelihood	AIC	BIC
Poisson	8	-336.47	688.93	716.29
NB	9	-278.58	575.16	605.94
ZIP	9	-335.00	687.99	718.78
ZINB[1]	10	NA	NA	NA
HP	9	-323.84	665.68	696.46
HNB	**10**	**-272.63**	**565.25**	**599.46**

[1]Failed to converge

Comparing the eligible series of Poisson models with the NB models (Table 7.2), the dispersion parameters (different from zero) and the likelihood ratio tests verified the existence of overdispersion as well as the appropriateness of the NB structure over the Poisson structure (Hosseinpour et al., 2014; Son et al., 2011). According to Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC), the HNB model achieved the best fit. The above-specified models were estimated using glmmTMB package in R (Brooks et al., 2017).

7.4 Results and Discussions

The estimation results of the final model are presented in Table 7.3.

Table 7.3 Estimation results of the HNB model

Variable	Estimate	SE	*p*
Binary part			
Fleet size	4.624	1.219	0.000
ARIA+	-0.631	0.207	0.002
Service type			
Route (ref.)			
Charter & Tour	-0.700	0.478	0.144
Other (Including school)	-1.300	0.586	0.027
Intercept	1.039	0.420	0.013
Count part			
Ln (Fleet total travel distance)	1.788	0.152	0.000
Fleet age			
Under 12 (ref.)			
Over 12	0.714	0.295	0.015
Roadworthy performance			
Above average (ref.)			
Below average	-0.449	0.248	0.071
Intercept	-0.804	0.276	0.004
α	2.2		
Log-likelihood at converge	-272.63		
Log-likelihood (intercept only)	-381.03		
Likelihood ratio test	$\chi^2(7)$= 216.81, *p*=0.000		
Number of observations	226		

Note: Only variables with at least one significant sub-category are presented in the table.

7.4.1 The Binary Part (Incident Risk)

The coefficients in the binary part were to represent an estimation of the probability of being non-zero so that a positive coefficient indicated a higher chance of having reported incidents.

The size of bus operators was positively associated with the probability of an operator having reported incidents. It is intuitive that large operators with more buses had high exposure to risks and were consequently more likely to report incidents while small operators with low exposure were associated with a lower risk of incidents.

Operators with lower ARIA+ score (metropolitan areas) were more likely to have reported incidents compared with those with higher ARIA+ score (regional areas). Independent of other factors, in areas of higher accessibility, traffic exposure is higher, and the road and traffic environments are usually more complex, resulting in a higher risk of incident occurrence. This reinforced previous findings that bus operation in urban areas is associated with higher accident risk (Chang & Yeh, 2005).

Operators providing non-route services were less likely to have recorded incidents than their route service counterparts. It is acknowledged that there are significant differences in operational characteristics between different bus service types. For example, route buses stop frequently, while tour/charter/school buses are mostly express services with few or no stops. According to the literature, a fair proportion of incidents occur near bus stops (e.g. 26% in af Wåhlberg (2002)), and bus stop density was positively associated with bus accident risk (Kelvin Chun Keong, 2017). Similarly, Huting et al. (2016) identified that local urban routes had about 56 percent higher odds of a crash compared with an express service which had fewer stops.

7.4.2 The Count Part (Incident Prevalence)

For a given variable with a positive coefficient, an increase in the value of the variable corresponded to an increment in the expected incident frequency and vice versa.

A close relationship between incident frequency and fleet total annual travel distance (exposure) was identified. Exposure has been found to be reliable predictors of incident frequency, and the close relationship added to the representativeness of the identified model (Kumara & Chin, 2005). The coefficient of *ln* (Fleet total travel distance) was larger than 1, indicating that increment in fleet total annual travel distance would result in an increase in incident rate (refer to (Moses & Savage, 1994) for a detailed illustration of the association between unity and the incident rate). A possible explanation arose during a focus group discussion with safety regulators and bus operators (Victorian bus operators, 2019): operators that travel more tend to have a higher awareness of the regulations relating to incident reporting and are more likely to have designated staff members and an established system for incident reporting, resulting in more reported incidents.

Controlling for other factors, operators with an average fleet age of under 12 years had fewer expected incidents than those with an average fleet age of over 12. This finding corresponds with intuitive expectations and a previous study which found that the proportion of vehicles less than five years old was positively associated with the safety performance of bus companies in Taiwan (Chang & Yeh, 2005). The explanation can be multidimensional: (1) operators with older fleets can be financially disadvantaged, which is associated with impaired safety performance (Naveh & Marcus, 2007); (2) drivers of older buses are more likely to be involved in crashes (Besharati & Tavakoli Kashani, 2018); (3) buses wear out and become less reliable (more failures in operation) with time, and older buses are not equipped with the same safety technologies as newer ones, which may increase their susceptibility to incidents (Chang & Yeh, 2005).

The coefficient of roadworthy performance suggested that operators with better roadworthy performance would have a higher expected incident frequency, which is contrary to our expectation. A possible explanation for this counterintuitive finding came from the focus group discussion with the safety regulators and operators (Victorian bus operators, 2019). Poorer fleet roadworthy performance tends to suggest an inadequate safety culture (Bus Safety Victoria, 2016), where incidents are not taken seriously, reported or recorded properly, which may result in neglecting and underreporting of incidents.

7.4.3 Limitations

A common issue with self-reported data in safety studies is underreporting (Kumara & Chin, 2005; Wretstrand, Holmberg, & Berntman, 2014). According to Blower (2017), the Motor Carrier Management Information System (MCMIS) crash file contained approximately two-thirds of the crashes that met the reporting criteria. During the focus group discussion with 13 representative Victorian bus operators (Victorian bus operators, 2019), it was agreed that the incident dataset managed by the state safety regulator did not contain all reportable incidents.

Examining the evidence from practitioners in the Victorian bus industry and the literature, the major causes of underreporting include both internal (the driver misreporting) and external.

Regarding internal mis- and under-reporting, Wretstrand et al. (2014) found that drivers frequently missed reporting accidents to the bus operators even though they might have resulted in moderate or severe injuries. The descriptions of some of the reported incidents in Victoria provided some evidence as well. By way of example, a bus company received this complaint from a passenger: "The bus collided with something and the window next to me shattered. I was covered in glass and I reported it to the driver. He didn't stop or check the damage. The damage got worse through the journey." (Transport Safety Victoria, 2018). Warmerdam et al. (2017) also identified a significant degree of underreporting by employees in Australian fleets, due in part to lack of training.

External or operator underreporting refers to the deficiencies in the transfer of reported incidents from internal records to the regulator. Blower (2017) identified that a substantial number of crashes that met the reporting criteria were recorded in motor carriers' internal records yet not contained in the reported crash file (MCMIS). External underreporting in the Victorian context can mainly be attributed to the inconsistency of the criteria of incident reporting and operators experiencing difficulty in interpreting the criteria. Bus incidents are self-reported while there is no systematic standard for reporting. Therefore, the standards vary significantly from operator to operator, even with an operation. One fleet manager described the challenge regarding incident reporting: "Sometimes people aren't sure. Do I report that? Is that an incident?".

In the context of this study, underreporting is likely to somewhat mask the relationships identified. It is logical to speculate that small operators in remote areas are more likely to underreport due to lack of designated staff or an established system for incident reporting, and less frequent contact with the safety regulators, respectively, which may interfere with the interpretation of their low incident risk being attributed to low exposure. As noted above, underreporting may also be responsible for the counterintuitive sign of roadworthy performance in incident prevalence.

The incident frequency was modeled on an aggregate level of four years as opposed to being year-specific, which failed to take into consideration the yearly variation in operational characteristics (e.g. travel distance, and fleet age). More reliable year-specific data on operational characteristics may help improve the accuracy and precision of the model.

In the safety analysis, it is optimal that as many relevant factors (driver, vehicle, carrier, environment) be obtained as possible (Stern et al., 2019). The existing datasets have only a limited number of variables recorded (Section 3.6), which may contribute to the omitted variable biases. As reviewed in Section 2.2, factors including organizational financial performance (Naveh & Marcus, 2007), driver characteristics (number of drivers (Hwang et al., 2019), driver/non-driver ratio (Chang & Yeh, 2005), the ratio of young/older drivers (Park, Kim, Kho, & Park, 2017), driver traffic violations (Cantor, Corsi, Grimm, & Özpolat, 2010; Chang & Yeh, 2005; Hwang et al., 2019), and bus configuration (Chimba et al., 2010; Huting et al., 2016; Liu, Boyle, & Banerjee, 2018) may also influence operators' safety performance and should be examined in future research.

7.4.4 Recommendations

Regarding the issue of excess zeros, it is worth mentioning that apart from the zero-altered approach scrutinized in Section 7.3.1.2, innovative models have been developed and applied to analyze count data of the sort, among which, the negative binomial-Lindley (Geedipally, Lord, & Dhavala, 2012; Lord & Geedipally, 2011; Shaon, Qin, Shirazi, Lord, & Geedipally, 2018) has demonstrated potential and can be a direction for future research.

To address the issue of underreporting, it is recommended that the criteria for incident reporting be made clear and consistent, efforts be made (e.g. audits, bus forums, safety campaigns, and newsletters) to ensure the message is well received among the operators and operators engage drivers in active incident reporting via training, monitoring (e.g. in-vehicle monitoring system to capture the occurrence of incidents), and implementation of safety culture (Bus Safety Victoria, 2016).

Regarding the need for more accurate data and the issue of potential omitted variables, the MCMIS serves as a good example. MCMIS, maintained by Federal Motor Carrier Safety Administration (2015), synthesizes datasets providing information on the crash, census, inspection and safety profile of motor carriers, which has enabled and benefited a number of studies examining factors affecting motor carrier safety performance, producing valuable insights (Chen, 2008; Corsi et al., 2012; Hwang et al., 2019; Monaco & Redmon, 2012; Moses & Savage, 1994). It is then recommended that statewide or nationwide efforts be devoted to collecting relevant information and forces be joint together to link datasets from different sources to establish a more comprehensive database to empower future research (Corsi et al., 2012).

7.5 Conclusions

This chapter set out to explore the impact of operational characteristics on the safety performance of bus operators using incident data of 226 bus operators in Victoria, Australia between 2014 and 2018. In order to arrive at the most accurate estimation of the effects of operational characteristics, the data structure was inspected, the derived methodological challenges examined, and the potential approaches explored. The HNB model was deemed most appropriate to fit the data, and the empirical results showed that it addressed the issues to a satisfactory extent.

In general, the findings were consistent with previous literature. Being a large, route operator or an operator providing service in areas of higher accessibility was found to be positively associated with the risk of having incidents. Among those which had at least one incident, fleet total travel distance and fleet age were found to be positively associated with incident frequency, while better fleet roadworthy performance was found to give rise to more incidents. The study highlighted the different effects of operational characteristics on incident risk and prevalence, offering more detailed insights than previously documented in the literature. Limitations of the study include underreporting of incidents, potential omitted variable bias, and lack of year specific operational characteristics. Recommendations for practice include clear and consistent incident reporting criteria be delivered, driver incident reporting be promoted, the establishment of a comprehensive database of heavy vehicle operators to empower future research, and specific efforts be spared for older fleets (Chimba et al., 2010; Chu, 2014; Feng et al., 2016; Goh et al., 2014a; Huting et al., 2016; Kaplan & Prato, 2012; Yoon et al., 2017).

Chapter 8 DISCUSSIONS AND CONCLUSIONS

8.1 Introduction

This research has been conducted to gain an in-depth understanding of the bus maintenance, roadworthy, and safety performance of the Victorian bus fleet using a multi-phased approach, including the questionnaire and data-driven analyses of inspection, maintenance, and incident data. This chapter concludes the thesis by providing a summary of the key findings that have emerged from the research and a discussion of the contributions to new knowledge, including both the theoretical and methodological inferences. It then examines the impact of the findings on improved practices for both regulators and practitioners in Victoria to enhance bus fleet performance. It closes with a discussion of the limitations and some suggestions for future research in this field.

8.2 Summary of Key Findings

The findings of this research are summarised within four major components: (1) a portrait of bus inspection outcomes, (2) the investigation of inspection and maintenance practices, (3) the identification and quantification of risk factors for bus inspection failures and (4) the identification of factors influencing fleet safety performance. The key findings are summarized in the following paragraphs.

Regarding the inspection and maintenance practices of bus operators in three jurisdictions in Australia, pre-trip inspections were widely conducted irrespective of the characteristics of the bus operator or the operator's perceptions of this inspection type. Time-distance based inspections had weaker recognition and implementation compared with the other two inspection types, with the practices being diverse. Mandatory, independent inspections varied in form and interval between jurisdictions, but were well acknowledged, although considered to have a considerable financial impost.

According to annual bus safety inspection data (Victoria: 2014-2018), at least one component failed at the time of presentation in 18 percent of inspections. Among the fourteen inspected component categories, the components with the highest failure rate were Steering & Suspension (6.8%), Body & Chassis (6.2%), Lamps, Signals & Reflectors (5.9%), Engine & Driveline (5.0%) and Brakes (4.1%).

The annual Victorian inspection outcome data analysis identified four distinct clusters exhibiting different inspection failure patterns—each with unique likelihood and magnitude of individual component failure—among the Victorian bus population: 'non-failure' (84.7%), 'lower-risk' (7.4%), 'higher-risk' (7.1%) and 'critical failure' (0.8%). The non-failure group had a near zero probability of failing any component, with most components passing. The lower- and higher-risk failure groups generally failed between one and four components, with the latter group having a higher probability of failing brake-related components. Finally, the critical failure group had the highest probability of failing every component and generally failed no fewer than five components per inspection.

This research not only constituted four operator types (Best (24%), Better (29%), Worse (31%), and Worst (16%) performers) based on their varying proportions of inspection failure patterns but also presented the level of inspection failure risk associated with individual operators. These results revealed the relative performance of bus operators and offered the baseline against which operators can benchmark.

Vehicle characteristics were found to have a profound impact on annual inspection outcomes. Vehicle age and odometer reading were positively associated with inspection failure risk. Every year increase in bus age resulted in an 8.0 percent increase in the odds of failing the annual inspection and every 100,000 kilometres increase in odometer led to an 8.1 percent increase in the odds of failure. Vehicle make played an important role in inspection outcomes, with the performance of different makes varying significantly. Vehicle configuration (and, by inference service type) was also associated with inspection failures, with coaches having higher odds (OR=1.2) of failing an inspection than buses.

Analysis of the recorded incident data revealed that, among those vehicles which had at least one incident, fleet total travel distance and fleet age were found to be positively associated with incident frequency.

Somewhat paradoxically, the better fleet roadworthy performance was found to give rise to more incidents, however, this was likely due to higher reporting rates among these operators.

Regarding the impact of operational characteristics on maintenance, roadworthy and safety performance, being a small, rural operator was associated with weaker recognition of the importance of time-distance based inspections and non-comparable inspection practices; the lowest inspection failure risk was observed among large operators, regardless of the location of operation; 'Best' and 'Better' type operators had a significantly higher proportion of large operators compared with the 'Worst' type and 'Better' type operators had a higher proportion of route operators compared with 'Worse' type; being a large, route operator or an operator providing service in areas of higher accessibility was found to be positively associated with the risk of having a higher number of reported incidents, which can be attributed to traffic exposure and potentially higher reporting rates.

8.3 Contributions to New Knowledge

The research work carried out has generated a number of original contributions to knowledge in the respective fields, as listed below.

Use of a structured approach in the development of an original research framework to examine bus roadworthy performance. Previous studies investigating bus roadworthy performance have been scattered and preliminary, with the majority focusing on applications in the US. This research represented an attempt to gain a comprehensive understanding of the bus roadworthy performance in Victoria, most notably with a systematic and detailed investigation of a large bus inspection dataset. The application of the research framework and the multi-phased structured approach adopted in this research are original and provide a good reference for other jurisdictions and peer industries (e.g. trucking).

Exploring and demonstrating the utility of bus annual inspection data in promoting a better understanding of bus roadworthy performance. Robust databases are vital for analyzing the current situation and informing evidence-based countermeasures. As reviewed in Section 2.4.2.3, there are inherent challenges in obtaining robust and uniform data across organizations (operators) to assess fleet roadworthy performance. This research demonstrated innovative analyses of annual bus inspection data, which contributed significantly to an enhanced understanding of bus roadworthy performance. The merits of the annual bus inspection data are presented in Section 3.4.2 and the findings drawn from the analyses based on inspection data have proven insightful. This thesis also exemplifies how this dataset can be incorporated with complementary data sources, e.g. operator profiles and incident datasets, to add more depth and breadth to the data-driven analyses.

Identifying patterns and profiles of Victorian bus inspection outcomes. Chapter 4 presented the development of a sophisticated approach to investigate the roadworthy condition of Victorian buses. The results identified not only distinct failure patterns but also the corresponding likelihood and magnitude of each, providing a comprehensive understanding of the overall roadworthy condition of Victorian buses.

An improved understanding of current inspection practices in the Victorian bus industry and the factors influencing them (Chapter 5). The majority of previous studies investigating the organizational factors influencing fleet maintenance practices have been conducted in North America. As a result, the validity of those outcomes is not known for other countries where the operating and regulatory environments are considerably different. This research has provided comparative research in Victoria, Australia, and revealed the current practices of bus inspections, identified issues in need of improvement, and pointed the way towards potentially tailoring inspection and maintenance practices to suit different operator types.

Improved estimation of the impacts on bus inspection outcomes of inspection, vehicle, and operator characteristics (Chapter 6). Although some previous studies have investigated the risk factors for inspection failures, most focused on emissions rather than roadworthiness. Moreover, they either examined private passenger vehicles only or did not differentiate between private and commercial vehicle ownership types. This research identified the factors contributing to bus inspection outcomes and quantified the effects attributable to inspections, vehicles, and operators respectively, extending past research and contributing to the knowledge in this area.

Realization of the hierarchical structure of bus inspection data and the consequent application of the multilevel modeling approach, yielding valuable insights (Chapters 4 and 6). From a methodological perspective, it was the first time that multilevel analyses have been applied to large-scale inspection data, satisfactorily addressing the challenges posed by the hierarchical data structure. The theoretical significance of this research is its accounting for the unobserved factors across bus operators, leading to a more accurate representation of reality. The classification (Chapter 4) and ranking (Chapter 6) of operators regarding their roadworthy performance informed the varying risk levels of operators, laying the groundwork for the selective targeting of operators to improve the overall roadworthy condition of the fleet.

An understanding of the effect of fleet roadworthiness on fleet incident outcomes in relation to other operational characteristics (Chapter 7). Previous research addressing bus safety has mainly focused on the region/state, route/road segment, or individual (incident/driver/vehicle) level, rarely taking the fleet setting of bus operation into account. Previous studies have also fallen short in adequately representing the impact of fleet roadworthy performance on safety outcomes, especially in relation to other risk factors, such as fleet size and service characteristics (Section 2.3). This research has made contributions in the area by establishing an understanding of the effect of bus roadworthiness in relation to other operational characteristics on fleet incident outcomes.

8.4 Limitations

While this thesis has provided several original contributions to knowledge, it is also subject to a number of limitations (as summarised in Table 8.1).

First, there are some issues with data availability and accuracy in this research, which have been discussed in the respective chapters and are summarised in the table below. Approximately 13 percent of the inspection data had missing or conflicting values, reducing the number of eligible records available for the analysis. Despite the efforts to gather a comprehensive set of operator-level information, operator-level data were restricted to three characteristics, due to the absence of a structured collection and management of bus operator information at the state level, potentially leading to omitted variable biases and limiting the explanatory power of the analyses. The nature of recording component failures irrespective of their implications on vehicle performance can bias the failure patterns identified in Chapter 4. The modeling in Chapters 6 and 7 was confined to the rough estimation of Vehicle Kilometres Travelled (VKT) while more detailed data like VKT by road class, speed distributions, and operating environments (which could be obtained via real-time vehicle position data) could add depth to future research efforts. The bus incident data, which were self-reported by bus drivers and operators, was subject to limitations of underreporting and the inherent inaccuracies related to self-reporting. This research attempted to explore the potential safety effects brought about by achieving a more roadworthy fleet but should be treated with some caution due to these limitations.

Table 8.1 A brief summary of the limitations

Reference	Issue	Representation
Section 3.5.6	Accuracy	13 percent of the integrated inspection data had missing or conflicting values
Chapter 4, 5, 6 & 7	Availability	A limited number of explanatory variables, especially at the operator level
Section 4.6	Accuracy	Severity differences in the consequences of the various component failure types are not captured by the inspection process.
Chapter 6 & 7	Accuracy	Lack of vehicle kilometres travelled by road class, speed distributions, operating environments, etc.
Section 7.4.3	Accuracy & availability	Underreporting of bus incidents

It is recommended that state or nationwide efforts be devoted to employing new technologies to collect data of higher quality (e.g. in-vehicle motoring system, GPS vehicle tracking system), supervising, monitoring and validating data collection and recording, promoting data uniformity across jurisdictions and helping the various agencies to work more closely together to integrate data from different sources to establish a more comprehensive database. This will allow a greater depth of understanding to be gained from future research.

A further limitation is the geographical and regulatory context of the research. The Victorian bus network has been constantly seeking to survive on private vehicle ownership (Cotter, 2018) as opposed to public or mixed ownership as in some other jurisdictions. Vehicle ownership status can impact on bus fleet performance (Cantor, Celebi, Corsi, & Grimm, 2013; Filippini & Prioni, 2003). Therefore, the findings presented in this thesis might not be entirely transferrable to jurisdictions where bus operational and regulatory aspects are different.

8.5 Implications for Bus Operation and Regulation

The results obtained in this research provide empirical support for regulators to update and expand regulatory regimes and activities and offer practitioners in the industry practical guidance to enhance the reliability and safety of bus operations.

It was found that every year increase in vehicle age resulted in an 8 percent increase in the odds of failing an inspection. An older fleet (older than a mean vehicle age of 12 years) was also found to have adverse effects on operator safety performance. Due to ongoing work on the Victorian rail system in recent years, the regular yet transitory demand for significant numbers of train replacement buses (Ilanbey, 2020) has led most operators to keep their vehicles for a longer period.

It is therefore recommended that regulatory efforts be devoted to:

- enforcing more stringent maintenance requirements for older buses,
- monitoring the reliable and safe performance of older fleets,
- devising and enforcing specific vehicle and fleet age restriction (Bus Industry Confederation, 2017) and

- allocating resources to update the fleet if necessary (Mathew, Khasnabis, & Mishra, 2010; Minister for Public Transport, 2018).

The identification of bus failure patterns, and the classification and ranking (Chapter 4 & 6) of operators regarding their roadworthy performance, can inform safety regulators of the varying probabilities of inspection failures operators and vehicles have. This information can facilitate more efficient follow-up with inspection failures and permit targeting of random roadside inspections or audits (Section 2.4.4), making better use of limited resources, reducing the burden of auditing buses and operators of low risk, and improving the efficiency of regulatory enforcement. In addition, the knowledge can be applied to industry mentoring activities where operators of the best practice are invited to impart their wisdom, translate the desirable features and share their expertise of bus operation and maintenance with other operators.

Synthesizing the impacts of operational characteristics, the fleet size of individual operators has received the most scrutiny and has been shown to influence maintenance, roadworthy, and safety performance. As illustrated in the respective sections, some of the findings arise from limitations in available resources and expertise, with size being a typical indicator of these. Large operators usually have more to invest in maintenance facilities, staff, technology, management proficiency, and the like. They are also likely to benefit from economies of scale, which can contribute to better fleet performance (Cantor et al., 2014). Smaller operators are more likely to run older, higher mileage buses, lack the ability or propensity to maintain buses to standard, and may rely on the annual inspection to pick up component faults or failures.

It is therefore recommended that operators with limited resources investigate resource sharing arrangements, such as the contracting of inspections and maintenance to a large regional operator or a Regional Maintenance Centre (Beruvides et al., 2009).

8.6 Areas for Future Research

There are several areas where the work of this thesis could be built upon to further advance bus maintenance, roadworthy and safety performance knowledge and practice. Some opportunities for future research are as follows:

The findings from this research presented a specific picture of the roadworthy condition of buses in Victoria during a four-year period. The approach developed in this research could be extrapolated to other jurisdictions and the national level. In view of efforts to achieve consistent inspections Australia-wide (National Heavy Vehicle Regulator, 2016), an integrated national database is achievable, and could be used to verify the results in Victoria, benchmark among jurisdictions, and inform heavy vehicle regulators of more effective countermeasures.

It is agreed among the research components that, apart from the operational characteristics examined, there are other factors that contribute to varying levels of roadworthy performance among operators. A preliminary gathering with practitioners revealed a variety of factors including the practice of pre-annual inspections, frequency of inspector visits, and personal relationships with inspectors. An in-depth investigation into some of the less tangible factors, such as safety culture, for example, would complement the primarily quantitative findings of this study.

Given that vehicles of certain characteristics (e.g. make, configuration) carried an elevated risk of inspection failure and some components were more prone to failure than the others, further research could explore the reasons for the patterns observed. In view of the fact that the frequency of mandatory, independent inspections both varies among jurisdictions (biannual vs annual) and sometimes between vehicles of different characteristics, a number of questions relating to mandatory independent inspections arise: What is the optimal frequency of mandatory independent inspections, should vehicles of certain characteristics be inspected more frequently, and should some components be inspected more often than others? These questions could be explored further as part of future research efforts.

On the one hand, the questionnaire indicated that mandatory, independent inspections were well acknowledged across operators. On the other, between 4 and 8.5 percent of inspections during the study period were conducted up to four weeks later than scheduled (Section 3.5.2). According to Assemi and Hickman (2018), heavy vehicles (including buses and trucks) with longer inspection intervals (indicating less attention to the periodic inspection of the vehicle) were more likely to be involved in a crash involving non-compliant driving behaviours. It is speculated that late inspections are associated with a less diligent attitude towards annual inspections and vehicle mechanical condition, along with unproficiency in operation and maintenance planning and management. It is therefore recommended that future research investigate the reasons for late annual inspections and the relationship between timely annual fleet inspection, roadworthy, and safety performance.

8.7 Final Discussion and Conclusion

In conclusion, this research has developed an in-depth understanding of the factors influencing bus fleet maintenance, roadworthy, and safety performance in Victoria, Australia. It presented a systematic, structured approach and a unique undertaking of analytical, statistical, and multilevel modeling, and is thought to make a significant contribution to the field. From a methodological perspective, this research demonstrated that it could be advantageous for inspection outcome modeling to adopt approaches that account for operator-specific effects as well as the unobserved factors that are likely to be present in the bus inspection outcome datasets. The findings presented the current bus fleet maintenance practices, roadworthy and safety conditions, informed the varying risk levels of operators regarding their roadworthy performance, and revealed the factors in play for fleet performance. The results obtained in this research have practical implications for safety regulators to update and expand regulatory regimes and activities and provide practitioners in the industry with empirical support and tangible guidance to enhance the reliability and safety of bus operations. Regarding the limitations, firstly, the research done was conducted within the context of the single jurisdiction of Victoria, Australia. Whether similar findings can be replicated in other jurisdictions where bus operational and regulatory aspects are different remains untested. Secondly, whilst the methodologies adopted in this research are considered robust, it is acknowledged that they are bounded by the limitations of the data to some extent. Given this, the work presented in this thesis provides much impetus for future research to build on the knowledge gained from this research to further advance the knowledge and practice in this field.

APPENDIX A

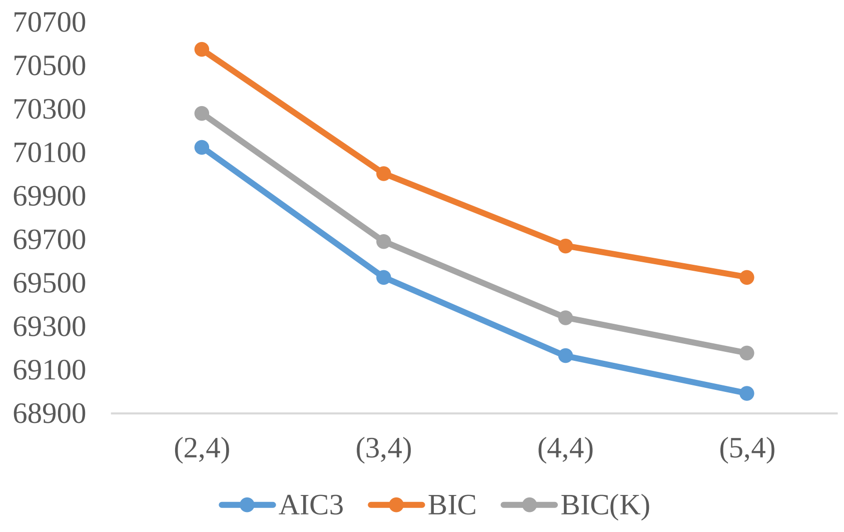

Figure 4.8 The change in information criteria

Table 4.7 Post hoc tests

p-value	Size (Large vs non-large)	Service (Route vs non-route)
Type 1 vs Type 2	0.707	0.454
Type 1 vs Type 3	0.013	0.013
Type 1 vs Type 4	<u>0.003</u>	0.313
Type 2 vs Type 3	<u>0.003</u>	<u>0.001</u>
Type 2 vs Type 4	<u>0.000</u>	0.097
Type 3 vs Type 4	0.298	0.250

APPENDIX B

Bus operator investigation

Thank you very much for choosing to participate in the survey.

Instructions

1. This survey is part of the investigator's PhD program, which tries to understand the **nature** of **current bus safety inspection regimes**. You will contribute to a study to help **improve** the inspection regimes, which is expected to benefit the bus industry and the community by **reducing inspection costs** and **improving vehicle safety**.

2. The questionnaire is composed of **six** sections.
   Section **I** is about the **characteristics** of you and your bus operation.
   Section **II** focuses on vehicle **inspection practice** in your company/depot.
   Section **III**, **IV** and **V** aim to understand your **perceptions** of the relationships between inspections and roadworthiness, safety and efficiency.
   Section **VI** welcomes your **comments** on bus safety inspections.

   Please fill in the questionnaire **to the best of your knowledge**. Since it involves information in **multiple aspects**, you are also encouraged to have a discussion with people in your fleet before you complete it. Your efforts will be greatly appreciated.

3. If your company has more than one depot, please answer on behalf of **your own depot.**

4. It will probably take you around **15 minutes** to complete the questionnaire.

5. Please be assured that all the information you provide will be **confidential. Ethics approval** has been granted by Monash University Human Research Ethics Committee, which can be accessed via the following link: https://goo.gl/RNXBzy.

6. For more information about the survey, please refer to the attached **Explanatory Statement**.

I. Operator and operation information

1. Please indicate your position in your company/depot.
   ☐Director
   ☐Fleet Manager
   ☐Other manager
   ☐Supervisor
   ☐Maintenance staff
   ☐Other, please specify: _______________

2. How long have you been working in the position? _______________ years
3. How long have you been working in the bus industry? _______________ years

4. Which state/ territory does your company/depot primarily operate in? (Please choose one)
   ☐Australian Capital Territory
   ☐New South Wales
   ☐Northern Territory
   ☐Queensland
   ☐South Australia
   ☐Tasmania
   ☐Victoria
   ☐Western Australia

5. The ownership type of your bus company/depot
   ☐Family owned
   ☐Part private/part public
   ☐Multinational enterprise
   ☐School/philanthropic organisation
   ☐Other

6. Type of operator
   ☐Accredited
   ☐Registered
   ☐Other, please specify: _____________

7. Are you contracted to the state/territory public transport coordinator to provide a bus service? (Example: PTV in Victoria, TransLink in Queensland, Transport for NSW etc.)
   ☐Yes ☐No ☐Don't know.
8. Is your company/depot a member of your state bus association?
   ☐Yes ☐No ☐ Don't know.
9. Main location of operation (Please choose one)
   ☐Metropolitan ☐Regional ☐ Rural
10. Which of the following bus services does your company/depot provide? (Tick all that apply)

    ☐ Route bus service
    ☐ School bus service
    ☐ Tour and charter bus service
    ☐ Airport bus service
    ☐ Intrastate and interstate coach service
    ☐ Community bus service
    ☐ Courtesy bus service
    ☐ Hire and drive bus service
    ☐ Other, please specify: _______________

11. Staff information

a. What is the approximate number of **drivers** in your company/depot? _______________
b. What is the approximate number of **maintenance staff (**If there are any) in your company/depot? _______________

12. Fleet information
    a. What is the approximate number of **buses** in your fleet? _______________
    b. Please also indicate the corresponding quantity of the listed bus types. (**Either** number **or** percentage will do)

Sizes	Number	Percentage
No more than 12 seats		
Between 13 and 24 seats		
Between 25 and 40 seats		
More than 40 seats		

    c. What is the average **age** of your bus fleet? _________________years
    (Please provide your best estimation)

13. What is the approximate number of **maintenance bays (**If there are any**)** in your company/depot? _______________
14. How many kilometres (in thousands) did your vehicles undertake in 2016? (**Either** the fleet total **or** the average per vehicle will do)

Total for fleet OR Average per vehicle

____________ ('000) ______________ ('000)

(Please provide your best estimation)

II. Inspection

1. If your company/depot offers different kinds of service, are there any differences in the way that you inspect the vehicles running different service types?

☐ Yes
☐ No
☐ Not Applicable

Pre-trip inspection

1.1 Does your company/depot have a Pre-trip inspection routine?

☐Yes (Please answer questions **1.2, 1.3 and 1.4**)

☐It depends on the service type of the vehicle (Please answer question **1.1.1**)

☐No (Please skip to question **1.5**)

☐I don't know (Please skip to question **2.1**)

1.1.1Which types of service does your company/depot undertake a **Pre-trip inspection** for the serving vehicles? (Tick all that apply)

☐ Route bus service
☐ School bus service
☐ Tour and charter bus service

☐ Airport bus service
☐ Intrastate and interstate coach service
☐ Community bus service
☐ Courtesy bus service
☐ Hire and drive bus service
☐ Other, please specify: _______________

Please answer questions 1.2, 1.3, and 1.4 based on the service vehicles **with** Pre-trip inspections and 1.5 based on service vehicles **without** them.

1.2 How often are **Pre-trip inspections** conducted in your company/depot?

☐Every departure from depot
☐Every day
☐Every week
☐Every other week
☐Every month
☐Other, please specify: _______________

1.3 Please indicate who is responsible for conducting **Pre-trip inspections** in your fleet? (Tick all that apply)

☐Fueler
☐Bus driver
☐Team of maintenance staff in your company/depot
☐Other, please specify: ___________

1.4 According to your experience, how long does an average **Pre-trip inspection** take?

_______________ minutes

1.5 Why aren't **pre-trip inspections** regularly conducted in your company/depot? (Please choose one)

☐It has few benefits.
☐It is time-consuming.
☐It is costly.
☐ It is not necessary for our fleet.
☐Other, please specify: ________________

Time/Distance based vehicle safety inspection

It is also referred to as maintenance in some states/territories, which is periodic and usually more frequent than annual.

2.1 Does your company/depot have a **Time/Distance based vehicle safety inspection** scheme?

☐Yes (Please answer questions **2.2 and 2.3**)

☐It depends on the service type of the vehicle (Please answer question **2.1.1**)

☐No (Please skip to question **2.4**)

☐Don't know (Please skip to question **3.1.1**)

2.1.1 Which types of service does your company/depot undertake a Time/Distance based vehicle safety inspection scheme for the serving vehicles? (Tick all that apply)

☐ Route bus service
☐ School bus service
☐ Tour and charter bus service
☐ Airport bus service
☐ Intrastate and interstate coach service
☐ Community bus service
☐ Courtesy bus service
☐ Hire and drive bus service
☐ Other, please specify: _______________

Please answer questions 2.2 and 2.3 based on the service vehicles **with** Time/Distance based vehicle safety inspections and 2.4 based on service vehicles **without** them.

2.2 How does your company/depot schedule your vehicles for **Time/Distance based vehicle safety inspections**? (Please choose the most applicable one)

☐By experience

☐Refer to the inspection scheme and manually schedule

☐Rely on a computerized recording and reminder system

☐When necessary

☐Other, please specify: _______________

2.3 Please indicate who is responsible for conducting **Time/Distance based vehicle safety inspections** for your fleet? (Tick all that apply)

☐Team of maintenance staff in your company/depot
☐Specialised maintenance & repair company
☐Other, please specify: _______________

2.4 Why aren't **Time/Distance based vehicle safety inspections** regularly conducted in your company/depot? (Please choose one)

☐It has few benefits.

☐It is time-consuming.

☐It is costly.

☐ It is not necessary for our fleet.

☐Other, please specify: ________________

Annual safety inspection

Annual bus safety inspections are referred to as roadworthy certificates (RWC) in some states/territories.

3.1.1 Are annual bus safety inspections compulsory in your state/territory?

☐Yes (Please answer question 3.1.2)

☐No (Please skip to question 3.3)

☐Don't know (Please skip to question 3.3)

3.1.2 Which guidelines/checklists are you using when preparing your vehicles for an **Annual safety inspection**? (Tick all that apply)

☐National Heavy Vehicle Inspection Manual (Please skip to question 3.2)

☐State/Territory roadworthiness requirements (Please skip to question 3.2)

☐Recommendations from manufacturers (Please skip to question 3.2)

☐Internal guidelines (Please answer questions 3.1.3 and 3.1.4)

☐Other, please specify: ______________________________ (Please skip to question 3.2)

3.1.3 You have indicated that you have internal guidelines. What is different about your own inspection guidelines/checklists compared with the others? Please specify.

____

____

3.1.4 Why do you feel the needs to have internal guidelines/checklists? Please explain.

____

____

3.2 Please indicate to what extent you agree or disagree with the following statements.

3.2.1 **Annual bus safety inspections** act as a strong incentive to maintain the fleet in roadworthy condition.

☐Strongly agree

☐Somewhat agree

☐Neither agree nor disagree

☐Somewhat disagree

☐Strongly disagree

3.2.2 If **annual safety inspections** were not mandatory, your company/depot would make significant changes to the maintenance practices.

☐Strongly agree

☐Somewhat agree

☐Neither agree nor disagree

☐Somewhat disagree

☐Strongly disagree

3.3 Currently, **mandatory independent inspections** are undertaken once a year in some states/territories. For safety, what do you think is the best interval for **mandatory independent bus inspections**?

☐Quarterly

☐Twice a year

☐Annual
☐Once every two years
☐Once every five years
☐Never
☐Other, please specify: ________________

III. Roadworthiness

1. How important do you think the following inspection types are to the **roadworthiness** of your bus fleet?

	Extremely important	Very important	Moderately Important	Slightly important	Not at all important
Pre-trip inspections	☐	☐	☐	☐	☐
Time/Distance based vehicle safety inspections	☐	☐	☐	☐	☐
Annual bus safety inspections	☐	☐	☐	☐	☐

2.1 How important do you think the following inspection types are in terms of their contributions to the **roadworthiness** of buses?

Section	Extremely important	Very important	Moderately Important	Slightly important	Not at all important
Brakes	☐	☐	☐	☐	☐
Steering	☐	☐	☐	☐	☐
Suspension	☐	☐	☐	☐	☐
Tyres/Wheels	☐	☐	☐	☐	☐
Body & Structure	☐	☐	☐	☐	☐
Engine & Driveline	☐	☐	☐	☐	☐
Seats & Seatbelts	☐	☐	☐	☐	☐
Lights & Reflectors	☐	☐	☐	☐	☐
Windscreen &Windows	☐	☐	☐	☐	☐
Accessories	☐	☐	☐	☐	☐

2.2 Please choose the **five** most important items and rank them from 1 (the most important) to 5 (the least important).

Section	Ranking
Brakes	
Steering	
Suspension	
Tyres/Wheels	
Body & Structure	
Engine & Driveline	

Seats & Seatbelts	
Lights & Reflectors	
Windscreen &Windows	
Accessories	

3. How roadworthy would you classify your fleet to be?
   ☐Excellent
   ☐Good
   ☐Average
   ☐Poor
   ☐Very poor
4. What's the proportion of vehicles in your fleet that pass the annual inspection on the first presentation?
   ☐ More than 95%
   ☐ Between 85% and 95%
   ☐ Between 75% and 85%
   ☐ Between 65% and 75%
   ☐ Less than 65%
   ☐ Not applicable

IV. Safety

1. Please rank the following factors according to your opinion of their contributions to bus accidents, with 1 being the most important and 4 being the least important.

☐ Road/environmental condition

☐ Vehicle defects

☐ Bus drivers

☐ Other road users (car drivers, motorcyclists, pedestrians, cyclists and etc.)

2.1 Has your fleet had any serious incidents that have needed to be reported to your regulator during the last 5 years? (Serious meaning emergency workers were called, the service had to stop)

☐Yes (Please answer question 3.2 and 3.3)
☐No (Please skip to the next section **Efficiency**)

2.2 How many serious incidents have there been in your fleet in the last 5 years? ____________

2.3 Did these serious incidents change your approach to vehicle inspections?

☐Yes. Please explain____
☐No. Please explain____
☐Not applicable

V. Efficiency

1.1 In your opinion, what is the **productivity** impact on your company/depot of the following inspection types?

Productivity impact	Major loss	Slight loss	None	Slight gain	Major gain
Pre-trip inspections	☐	☐	☐	☐	☐
Time/Distance based vehicle safety inspections	☐	☐	☐	☐	☐
Annual bus safety inspections	☐	☐	☐	☐	☐

1.2 In your opinion, what is the **financial** impact on your company/depot of the following inspection types?

Financial impact	Major loss	Slight loss	None	Slight gain	Major gain
Pre-trip inspections	☐	☐	☐	☐	☐
Time/Distance based vehicle safety inspections	☐	☐	☐	☐	☐
Annual bus safety inspections	☐	☐	☐	☐	☐

VI. Comments

Do you have any further comments on bus safety inspections?

Acknowledgements

Thank you very much for completing this survey.

If you would like more information or to be sent aggregated results once the research is completed, please contact Jocelyn Qiu at (03) 9905 1858 or email Jocelyn.Qiu@monash.edu.

If you have an interest in participating in future investigations, please leave the following information.

Email address: ____________________________________

Name of bus operation: ____________________________

Please be assured that the information you provide will only be used to help further research. Your individual survey responses will not be released to anyone.

EXPLANATORY STATEMENT

Project: Understanding the relationships between bus operations, maintenance and safety

Chief Investigator's name: David Logan
Monash University Accident Research Centre (MUARC)
Phone: 03 9905 4376
email: David.Logan@monash.edu

Student's name: Jocelyn Qiu
Sustainable and Effective Public Transport-Graduate Research Interdisciplinary Program (SEPT-GRIP) / Monash University Accident Research Centre (MUARC)

Phone : 03 9905 1858
Email : Jocelyn.Qiu@monash.edu

You are invited to take part in this study. Please read this Explanatory Statement in full before deciding whether or not to participate in this research. If you would like further information regarding any aspect of this project, you are encouraged to contact the researchers via the phone numbers or email addresses listed above.

What does the research involve?

The implementation of comprehensive bus safety inspections is an important issue for road safety. This survey is targeted at bus operators who are directly responsible for bus safety inspections. The investigation will yield first-hand information of how safety inspections are implemented and operators' attitudes towards the relationship between inspections and roadworthiness, safety and efficiency.
You will be asked to complete the questionnaire based on your knowledge and experience.

Why were you chosen for this research?

We are inviting all accredited and registered bus operators to participate in this research.

Consenting to participate in the project and withdrawing from the research

Participation in the study is voluntary and you can withdraw at any time prior to submission. You don't need to answer every question in the questionnaire but your best attempt will be appreciated. Once you have submitted the questionnaire, your survey responses will be retained for the data analysis for a period of five years unless you ask us to delete them earlier.

Possible benefits and risks to participants

This survey is part of the investigator's PhD program, partly funded by a Bus Association Victoria scholarship, aiming to understand the nature of current bus safety inspection regimes. Your responses will contribute to a study aimed at improving the effectiveness and efficiency of inspection regimes, which is expected to benefit the bus industry and the community by reducing inspection costs and improving vehicle safety.

The questionnaire is going to be used to collect information from bus operators. You will be presented with a series of questions focusing on your knowledge and experience. The average time to complete the questionnaire is between 15 to 20 minutes. Nothing more than a modest imposition on your time is expected from participation in the survey.

Confidentiality

Your survey data will be securely stored at Monash University and will only be used to help understand inspection practices and attitudes. Your individual survey responses will not be released to anyone other than the researchers.

The investigation results will comprise one aspect of the investigator's thesis and may be published at a relevant conference or in a journal publication. Only results in aggregate format will be reported, and no individual can be identified in any publications made by the investigators.

Storage of data

The data from paper-based questionnaires will be entered into the online survey system, which, along with the data collected by the online platform will be password-protected. The paper-based questionnaires will then be shredded and disposed of in a confidential way.

The information will be retained for a duration of 5 years, in accordance with Monash University regulations. After this time, all information will be destroyed in an appropriate manner.

Results

It is expected that the results will be available in a year. Apart from being included in the investigator's thesis, they may also get published in a conference or a journal. You are welcome to contact the investigators via the contact details provided to request any publications.

Complaints

Should you have any concerns or complaints about the conduct of the project, you are welcome to contact the Executive Officer, Monash University Human Research Ethics (MUHREC):

Executive Officer
Monash University Human Research Ethics Committee (MUHREC)
Room 111, Chancellery Building E,
24 Sports Walk, Clayton Campus
Research Office
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Thank you,

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APPENDIX C

According to Table 6.5, some makes have predominant or exclusive body builders (Higer, King Long, Yutong, BCI, Toyota, and Mitsubishi) and others use a mix. Considering the dependence of vehicle body on make, it was omitted in the model.

Table 6.5 Cross tabulation between vehicle make and body

Vehicle body / Vehicle make	Volgren	Other Australian body builders	Higer/King Long/Yutong/BCI	Arakawa	Mitsubishi	Others	Total
Volvo	926	387	0	0	0	20	1,333
Scania	762	598	173	0	0	70	1,603
Mercedes Benz	403	847	62	0	0	51	1,363
Man	49	277	40	0	0	163	529
Iveco	88	129	0	0	0	60	277
Higer/King Long/Yutong/BCI	0	0	233	0	0	0	233
Toyota	0	0	0	462	0	0	462
Hino	18	310	40	0	0	10	378
Mitsubishi	1	0	0	0	445	0	446
Others	7	165	12	0	0	33	217
Total	2,254	2,713	560	462	445	407	6,841

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