INVESTIGATING THE BENEFITS OF CONSIDERING THE PAYLOAD SPECTRA OF FREIGHT VEHICLES ON PAVEMENT COSTS BASED ON WEIGH-IN-MOTION DATA

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ABSTRACT

Truck traffic is a crucial factor that contributes to pavement damage. The urbanization and globalization promote the higher level of daily consumption for goods, thus increasing the derived demand for freight transport. In some countries, such as Australia, there is a trend towards using larger vehicles, which raised the road authorities’ concern about their effect on pavement because of the lack of pavement maintenance and rehabilitation funding. Therefore, it is important to have a comprehensive understanding of Australian road freight market and optimize the allocation of freight for different types of trucks to reduce the total pavement damage.

Weigh-in-motion (WIM) system, which measures and records detailed vehicle information operating on road, was the data source for this study. The data was provided by the State Road Authority of Victoria (VicRoads). This thesis gave out a prototype filtering strategy for WIM database to improve the accuracy. Also, it investigated the efficiency of freight transport by comparing the effect of six-axle semi-trailers and nine-axle B-doubles with regards to pavement performance when carrying various payloads. Mathematical models were developed to help decision makers consider how to distribute the road freight task more efficiently to minimize the pavement damage induced by freight vehicles. A simplified pavement performance prediction model was utilized as a basis to determine the future pavement maintenance & rehabilitation schedules and thus, help compare the long-term pavement treatment costs for different traffic loading scenarios.

The outcomes of the research showed that it would have considerable advantages in reducing the overall pavement damage by decreasing the percentage of empty trucks, changing the proportion of freight carried by B-doubles as well as optimizing the payload...
distributions. In addition, there would be significant benefits in the pavement maintenance & rehabilitation costs over the pavement service life by improving the allocation of freight for trucks.
DECLARATION

This is to certify that:

1. The thesis comprises only my original work towards the degree of Master of Philosophy except where indicated in the Preface;
2. Due acknowledgement has been made in the text to all other material used;
3. The thesis is less than 50,000 words in length, exclusive of tables, maps, bibliographies and appendices.

15 December 2017

[Signature]
 PREFACE

This thesis has been written at the department of Infrastructure Engineering, The University of Melbourne. Each chapter is based on manuscripts which are published or submitted for publication. I declare that I am the primary author and have contributed to more than 50% of these papers.

**Journal paper submitted for potential publication:**


**Conference paper:**

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Melbourne, Australia

December 2017
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<th>Full Form</th>
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<tbody>
<tr>
<td>AASHTO</td>
<td>American Association of State Highway and Transportation Officials</td>
</tr>
<tr>
<td>ARRB</td>
<td>Australian Road Research Board</td>
</tr>
<tr>
<td>ASTM</td>
<td>American Society for Testing and Materials</td>
</tr>
<tr>
<td>BIRTE</td>
<td>Bureau of Infrastructure, Transport and Regional Economics</td>
</tr>
<tr>
<td>ESA</td>
<td>Equivalent Standard Axles</td>
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<tr>
<td>FY</td>
<td>Financial Year</td>
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<tr>
<td>HSEMU</td>
<td>High Speed Electronic Mass Unit</td>
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<tr>
<td>IRI</td>
<td>International Roughness Index</td>
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<tr>
<td>GVM</td>
<td>Gross Vehicle Mass</td>
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<tr>
<td>LSEMU</td>
<td>Low Speed Electronic Mass Unit</td>
</tr>
<tr>
<td>LTPP</td>
<td>Long-term Pavement Performance</td>
</tr>
<tr>
<td>MEPDG</td>
<td>Mechanistic Empirical Pavement Design Guide</td>
</tr>
<tr>
<td>NHVAS</td>
<td>National Heavy Vehicle Accreditation Scheme</td>
</tr>
<tr>
<td>M&amp;R</td>
<td>Maintenance &amp; Rehabilitation</td>
</tr>
<tr>
<td>PCR</td>
<td>Pavement Condition Rating</td>
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<td>PCS</td>
<td>Pavement Condition State</td>
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<tr>
<td>PDF</td>
<td>Probability Density Function</td>
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<tr>
<td>Abbreviation</td>
<td>Description</td>
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<tr>
<td>PSI</td>
<td>Present Serviceability Index</td>
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<tr>
<td>PSR</td>
<td>Pavement Serviceability Rating</td>
</tr>
<tr>
<td>PV</td>
<td>Present Value</td>
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<tr>
<td>SAR</td>
<td>Standard Axle Repetitions</td>
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<tr>
<td>VicRoads</td>
<td>the State Road Authority of Victoria</td>
</tr>
<tr>
<td>WIM</td>
<td>Weigh-in-motion</td>
</tr>
<tr>
<td>WRR</td>
<td>Western Ring Road</td>
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</table>
1 INTRODUCTION

1.1 Background to the study

Australia is a vast country with a small population, which was about 24.7 million in December 2017 (ABS, 2017). The number of people per kilometre of road is among the lowest in the developed world. Though the population is limited, this nation is one of the most urbanized countries worldwide. There is approximately 80 percent of the total population living in urban areas. The two largest cities, Sydney and Melbourne, gather nearly 40 percent of people (Austroads, 2005). The urbanization and globalization promote the higher level of daily consumption for goods, thus increasing the derived demand for freight. Both international and domestic freight movements are closely relevant to the economic growth of this nation (BITRE, 2010).

Transport infrastructure is a vital asset that makes a significant contribution to Australia’s economic performance and international competitiveness. Road transport is the dominant mode for freight movements within the country. It is recorded that road freight transported over 70 percent of the total 2,930 million tonnes of Australian domestic freight in financial year (FY) 2010. The road freight task in tonne-kilometres has grown dramatically in the past decades, which increased six-fold between 1971 and 2007, equivalent to average annual growth of approximately 5.75 percent per annum. Also, it is projected that the total freight task in Australia will continuously increase in the future, nearly doubling that of 2010 by 2030 and triple by 2050 (BITRE, 2010, ATA, 2013). As such, the number of freight vehicles on roads is also expected to grow (DIRD, 2014).
Besides, Australia is the most intensive user of road freight on a tonne-kilometre per person basis (Austroads, 2005, BITRE, 2010).

To relieve the burden of road freight transport, the trucking industry in Australia has changed significantly, which has the trend of shifting towards larger vehicle fleets (Figure 1-1). Among all the types of freight vehicles, the usage of B-doubles has increased dramatically in Australian market since 1990s. B-doubles have replaced the role of other popular trucks, such as six-axle articulated trucks in the road freight transport market. Also, it was estimated by Bureau of Infrastructure, Transport and Regional Economics (BIRTE) that B-doubles will continue to play a predominant role in the freight transporting industry in the future (BITRE, 2011b). The prevalence of B-doubles is mainly due to their current broad coverage of Australia’s road network. They are now allowed to operate on all inter-capital routes and most urban arterial roads. As an illustration, B-double road network in Melbourne is given in Figure 1-2.

![Figure 1-1: Total road freight by broad vehicle type and vehicle axle configuration, 1971-2007 (BITRE, 2011b)](image-url)
Although the application of larger freight vehicles gives an opportunity for relieving the burden of freight transport and traffic congestion, road authorities are concerned about their impact on the health of pavement because of their frequent road activities. Truck traffic (freight vehicle) is one of the most crucial factors for pavement damage and deterioration (Austroads, 2008, Austroads, 2012). Australian government spends billions of dollars on managing road network per annum. Among the total expenditure, a considerable percentage is utilized for road maintenance and rehabilitation activities (BITRE, 2011a, BITRE, 2016).

As a result of high demand for road freight transport and budget shortfalls in the pavement repair, it is necessary to have a comprehensive understanding of current Australian road freight market and help decision makers distribute the freight for different types of trucks efficiently. The following questions are required to be answered and investigated:

**Figure 1-2: B-double Road Network in Melbourne: Approved-green, Conditionally Approved-orange and Restricted-red (VicRoads, 2017)**
• What is the share of road freight in terms of weight and the payload distributions by truck class in current Australian trucking market?

• What is the impact of trucks with different configurations of axles and payload levels on pavement?

• What are the benefits in pavement performance by means of rearranging the freight share and payload spectra of freight vehicles?

1.2 Research hypothesis

The hypothesis of this research is that:

The total pavement damage can be reduced through optimizing the assignment of freight carried by trucks, such as considering the percentage of empty trucks, changing the proportion of freight transported by vehicle class as well as optimizing the payload distributions and thus, save the costs of pavement treatments in the long run.

1.3 Specific research aims

To improve the understanding of the impact of trucks on pavement structure and optimize the allocation of freight, the concept of equivalent standard axles (ESA), a well-developed and widely-adopted term, was applied to quantify the damage induced by trucks. ESA can convert the effect of trucks having different types of axles (single axle, tandem axles and triaxles) with various loading magnitude into the equivalent number of standard load that would produce the same amount of pavement distress. The standard load represents an axle with dual tyres applying an axle load of 80 kN on the pavement (AASHTO, 1993, Austroads, 2008, Austroads, 2012).
In addition, WIM database was utilized for this study as it can provide detailed information about vehicles operating on roads without interrupting the traffic flow. WIM system consists of records of site, date, vehicle speed, vehicle configuration (number of axles, number of axle groups and vehicle pattern), weight information (tare weight, legal weight limitation, gross vehicle mass (GVM), individual weight of axles and axle groups) as well as ESA (Thompson et al., 2016, Ren et al., 2016).

The overall objectives of this study are as follows:

1. To create a prototype for filtering WIM database and analyse the data to study the characteristics of trucks operating on road;
2. To investigate and compare the impact of different vehicle types on pavement infrastructure when carrying various payloads;
3. To minimize the total pavement damage by optimizing the allocation of freight undertaken by trucks based on WIM data;
4. To calculate the cost savings in the multi-year pavement maintenance & rehabilitation activities by applying the optimized distribution of freight.

1.4 Thesis structure

This thesis will include 6 chapters:

- Chapter 1 – Introduction
  specifies the background and the objectives of the thesis
- Chapter 2 – Literature review
  reviews the relevant background for this research. It mainly presents the principle and applications of WIM technology. In addition, the definition of pavement
damage and various types of pavement performance prediction models are listed as well.

- Chapter 3 – Data filter and analysis

describes the data source used for this research. A prototype of filtering WIM data is introduced in detail. Besides, some preliminary data analysis is conducted to investigate the features of the current freight transport market in Australia.

- Chapter 4 – Optimization of payload spectra for semi-trailers and B-doubles

develops mathematical models to optimize the assignment of freight with regard to pavement damage. The efficiency of B-doubles and semi-trailers transporting the freight is compared. In addition, the impact of the percentages of the empty trucks, the payload distributions and the proportions of freight carried by B-doubles on pavement damage is studied in depth.

- Chapter 5 – Cost savings in pavement maintenance and rehabilitation activities

presents a case study for investigating the potential advantages in pavement treatment activities for different ESA scenarios. A simplified flexible pavement performance prediction model is applied as a basis to determine the timing of future pavement maintenance and rehabilitation activities. The present value consisting of pavement repair costs and salvage value is calculated to quantify the benefits from the optimized freight distribution for trucks.

- Chapter 6 – Conclusions

summarizes the major findings of this research. It also highlights limitations of the current work, suggests other potential applications, and offers recommendations for future research.
2 LITERATURE REVIEW

2.1 Introduction

A comprehensive literature review was conducted in this chapter to help structure the research background & methods and strengthen the knowledge for this study. The principle of WIM technology and their applications by different scholars are mainly introduced. Chapter 2 also explores the approach of quantifying the pavement damage induced by vehicles with various axle group configurations and loads. In addition, some typical pavement performance prediction models are listed, which mainly have two streams, i.e. deterministic and stochastic models. The literature review draws on both academic and non-academic publications, including journal and conference papers, books, industry and research reports, as well as websites. Chapter 2 can be divided into the following sections:

- Section 2.2 introduces the development of WIM systems, the mechanism of WIM technology as well as studies based on WIM data.
- Section 2.3 illustrates the means of calculating the individual truck factor
- Section 2.4 presents two kinds of pavement performance prediction models
- Section 2.5 is the conclusion of this chapter

2.2 WIM technology

The definition of a WIM system is: ‘a device that measures the dynamic axle weight of a moving vehicle to estimate the corresponding static axle mass’ (Austroads, 2000)
2.2.1 A brief history of WIM systems

The idea of WIM technology was first introduced in the 1950s. The United States Bureau of Public Roads developed an electronic weighing device which can get the information of axle weights, axle spacings as well as vehicles operating at normal speeds on highways. The load cells were put into a reinforced concrete platform which was embedded into the surface of pavement (Norman and Hopkins, 1952). The Australian Road Research Board (ARRB) research team started to investigate the means of weighing vehicles travelling at highway speeds in late 1960s and early 1970s and developed the first WIM system - a Low Speed Electronic Mass Unit (LSEMU) that consisted of a plate supported by four load cells. On the basis of the experience with LSEMU, the first generation High Speed Electronic Mass Unit (HSEMU) was successfully developed afterwards (Koniditsiotis, 1995, Konidisiotis et al., 1995). Australia has also taken the lead in the research of strain gauge weighing sensor systems. The Main Roads Department-Western Australia developed a system called AXWAY which could measure the axle weights of vehicles operating at highway speeds using bridges as large dynamic scales (Peters, 1984). Following the experience of AXWAY WIM system, the Main Roads Department-Western Australia in collaboration with ARRB developed another system named CULWAY, which was less expensive to purchase and operate compared to AXWAY. The CULWAY system utilized road culverts as dynamic scales rather than bridges (Peters, 1986). Apart from AXWAY and CULWAY, other WIM systems from overseas have been introduced into Australia since the late 1970s (Koniditsiotis, 1995, Konidisiotis et al., 1995).

Currently, there are 134 WIM sites and 18 WIM system types throughout Australia. Maps of the locations of WIM sites are shown from Figure 2-1 to Figure 2-3 (Austroads, 2016).
Figure 2-1: WIM network- New South Wales, Victoria, Queensland, South Australia, Tasmania, Australian Capital Territory (Austroads, 2016)
Figure 2-2: WIM network- Western Australia (Austroads, 2016)
Figure 2-3: WIM network- Northern Territory (Austroads, 2016)
Among all the WIM systems, CULWAY is the most widely used traffic data collection system which is installed in many sites on intercity, urban freeway, rural and urban arterial routes around Australia (Grundy et al., 2002, Mitchell, 2010).

2.2.2 The components and advantages of WIM system

WIM systems are normally sorted into two broad groups, namely low speed (less than or equal to 15km/h) and high speed (greater than 15km/h), which is due to the requirement for functionality and accuracy. Either of the two categories is generally comprised of four basic components given in Figure 2-4: mass sensor, vehicle classification and/or identification sensor, processor and data storage unit, and user communication sensor. The mass sensor is the most important and fundamental component of a WIM system (Austroads, 2000). The mechanism of the WIM system is using sensing technology for the collection of traffic data. In details, the sensors embedded under the surface of pavements or bridges will be triggered when a vehicle passes the WIM site and then the signals illustrating the vehicle information will be generated. All the traffic data will be stored in a data acquisition unit that is capable of off-site analysis (Thompson et al., 2016).
WIM technology can effectively overcome the disadvantages of traditional static weigh stations where vehicles are weighed while at rest on scales. Firstly, WIM systems can collect different vehicle information at the same time, which can only be achieved by multiple types of static scales ranging from those that can weigh the GVM to those that weigh the axle groups. In general, the recorded WIM data includes various vehicle information, such as site, date, vehicle speed, vehicle configuration (number of axles, number of axle groups and vehicle pattern), weight information (tare weight, legal weight limitation, GVM, individual weight of axles and axle groups) as well as ESA calculated by recorded loads and standard loads based on the fourth power law. ESA is an important vehicle information, which is used for representing the pavement damage caused by trucks. The detailed concept of ESA will be explained in section 2.3. Also, the feature of automatic collection for WIM systems can avoid the potential safety risk for staff working at static weigh stations. Besides, each vehicle passes WIM site can be recorded whereas
weigh stations usually select only a limited sample of vehicles from traffic stream which may lead to bias. In short, WIM systems can provide a safer, more efficient, quicker and continuous way for collecting vehicle data (Austroads, 2000, Farkhideh et al., 2014, AppliedTraffic, 2013).

2.2.3 Applications of WIM data use

WIM technologies have been applied for a range of tasks, including the investigation of WIM accuracy, pavement and bridge design, the effect of overloaded vehicles and other applications. These different applications in the literature are discussed in detail as follows:

2.2.3.1 WIM accuracy

To check the accuracy of the WIM data as well as the effect caused by the measurement bias, researchers have carried out relevant studies of WIM sites in different jurisdictions.

Zhi et al. (1999) evaluated the historic performance of WIM systems in Manitoba, Canada. It is found that there are large numbers of unreliable vehicle data produced by WIM systems. Besides, the matched vehicle data from a WIM site at Brokenhead and a nearby truck weigh station at Westhaw were particularly investigated. It is noted that the WIM axle spacing data were outside the 95% tolerance range specified by the American Society for Testing and Materials (ASTM). Also, the vehicle classification data for vehicles with 5 to 9 axles were more accurate than that of 2 and 3 axles vehicles. Compared to the truck weights of the static weigh stations, 90% of the corresponding WIM records were underestimated and the degree of the errors were significant. Tarefder and Rodriguez-Ruiz (2013) evaluated the quality of WIM data from three bending plate sites and twelve piezoelectric sites installed in New Mexico based on the traffic
monitoring guide criterion. It is proved by the researchers that the bending plate WIM systems provided higher quality data than piezoelectric systems. The researchers thought this may be due to the lack of calibration or the effect caused by the surface condition and temperature in piezoelectric sensors. The accuracy of the WIM measurements for six highway sites in Alberta was studied by Farkhideh et al. (2014). The WIM data were from a five-year experiment that made a test truck with predetermined axle loads pass over these sites for 10 times per month. It is found by the researchers that the weight of the individual axle groups as well as the GVM of most sites exceeded the tolerance range of ASTM E1318 requirements though the speed and dimensions of the vehicle could be accurately measured.

Apart from the studies about the level of WIM accuracy, the factors leading to the measurement bias were also investigated. Alavi et al. (2001) and Gajda et al. (2013) checked the relationship between the temperature and the performance of piezoelectric WIM sensors. White et al. (2006) discovered that the quartz piezoelectric sensors were not sensitive to temperature and could provide reliable and stable vehicle weight data over time if embedded properly and provided enough structural support in the flat pavements. The influence of the pavement conditions in piezoelectric WIM sensors were also recognized by Farkhideh et al. (2014). But these researchers also mentioned their high sensitivity to carriageway’s traffic characteristics. In general, there are three major types of errors affecting the reliability of a WIM system, which are listed as follows: (1) actual error, associated with the error in determining the true mass of a vehicle; (2) systematic error, linked with flawed initial or drift in the calibration; (3) random error, associated with vehicular characteristics and WIM system errors (Austroads, 2000).
Additional investigation of the impact of WIM measurement bias on pavement design procedure was conducted by different researchers as well. Prozzi and Hong (2007) checked the influence of two types of WIM errors (random error due to WIM scale intrinsic properties and systematic error due to the calibration of WIM system) in the estimation of load-pavement impact. In this study, it is shown that random error contributes to overestimation of the load-pavement impact. Also, WIM system calibration is proved to be more important as the load-pavement impact calculation is more sensitive to systematic error than random error. The impact of WIM measurement bias on the predicted pavement performance (cracking, rutting and international roughness index (IRI)) for pavement design using the mechanistic empirical pavement design guide (MEPDG) was evaluated by Tarefder and Rodriguez-Ruiz (2013) and Farkhideh et al. (2014).

2.2.3.2 Infrastructure design

Another major branch of WIM applications is pavement and bridge design. In 1993 American association of state highway and transportation officials (AASHTO) pavement design guide, WIM data is one of the most important sources for predicting the traffic loading (i.e. the number of ESA) over the design period (AASHTO, 1993). With the development of MEPDG, all the default traffic information in this guide is from long-term pavement performance (LTPP) database utilizing the WIM systems throughout the united states and Canada. These data are also used for calibrating the pavement distresses models in the MEPDG. The full traffic characteristics are required to determine the axle loads which are applied on the pavement in each time increment of the damage accumulation process. To specify, the typical traffic data included in the WIM for the MEPDG are sorted as follows (NCHRP, 2004, Li et al., 2011):
• Truck traffic volume: in the base year and the growth rate over the design life
• Truck traffic directional and lane distribution factors
• Hourly and monthly traffic volume adjustment factors
• Axle load spectra and vehicle class distribution
• Other traffic information: vehicle speed, axle and wheelbase configurations, tire characteristics and inflation pressure.

Similarly, WIM database is also a critical traffic monitoring source for Australian pavement design guide (Austroads, 2008, Austroads, 2012).

Many scholars analysed the WIM database of different sites for the better development of the MEPDG. For instance, Timm et al. (2005) and Haider and Harichandran (2009) used mixed distribution models of two or more theoretical distributions to fit the axle load spectra to develop some representative site-specific axle load distributions models for the MEPDG. The importance of developing the better grouping scheme for WIM sites with similar truck characteristics was pointed out by Ishak et al. (2010) and Kweon and Cottrell Jr (2011). Also, state-wide truck traffic adjustment factors were investigated by Tran and Hall (2007b) while Sayyady et al. (2010) focused on the regional level. In addition, axle load distributions with different input levels (site-specific level, regional average, state-wide and MEPDG default values) are built by many researchers. Also, sensitivity analysis by comparing the difference of predicted pavement performance resulting from different input levels of axle load spectra were conducted in these studies (Lu and Harvey, 2006, Timm et al., 2006, Wang et al., 2007, Tran and Hall, 2007a, Li et al., 2009, Abbas et al., 2014).
2.2.3.3 Overloaded vehicles

To avoid the excessive damage to infrastructure caused by overloaded vehicles, the proportion of the overloaded trucks and the probability distributions of vehicle loads greater than legal limit can be detected by WIM systems (Austroads, 2000). There have been past studies related to overloaded vehicles and their impact on pavements or bridges (Mohammadi and Shah, 1992, Zhao et al., 2012, Pais et al., 2013, Rys et al., 2016, Lou et al., 2016). Mohammadi and Shah (1992) applied mixed distribution models to represent the truck load spectra, which can be used to estimate the frequency of occurrence of overloading in the transportation facilities and therefore determine the portion of damage induced by overloads. According to Zhao et al. (2012), the prediction of pavement distress in MEPDG was dependent on axle load spectra and closely relevant to the percentage of overloaded vehicles. It was discovered by these researchers that among the various types of distress, pavement rutting was least sensitive to the variations of axle load spectra, which indicated that it was least sensitive to the variations in the proportion of overloads (Zhao et al., 2012). The effect of overloaded vehicles on pavement was studied by Pais et al. (2013) who investigated the truck factor of different vehicles operating on various types of pavements. The influence of overloading in pavement construction and maintenance costs was revealed as well. It is found that the presence of overloaded trucks can increase the cost by more than 100% in comparison to the same vehicles with legal weight. In addition, the extent of the decrease of pavement fatigue life caused by overweight trucks was quantified by Rys et al. (2016). Apart from pavement, Lou et al. (2016) analysed the effect of overloaded vehicles on the service life of concrete bridge decks.
In conclusion, there have been wide applications of WIM systems in the literature. However, limited studies have focused on the usage of WIM data in freight movement and plan.

2.3 Truck factor

To quantify the pavement damage caused by vehicles with different configurations and loads, truck factor is required to be estimated, which means the number of standard axle repetitions (SAR) per vehicle. The standard axle is expressed as a single axle with dual tyres applying an axle load of 80 kN to the pavement. The SAR is calculated as follows (Austroads, 2008, Austroads, 2012):

\[
SAR_{mj} = \left( \frac{L_{ij}}{SL_i} \right)^m
\]  

(2-1)

where:

\( SAR_{mj} \) = number of SAR (or passages of the standard axle) which causes the same amount of damage as a single passage of axle group type \( i \) with load \( L_{ij} \), where the load damage exponent is \( m \)

\( SL_i \) = standard load for axle group type \( i \)

\( L_{ij} = j^{th} \) load magnitude on the axle group type \( i \)

\( m \) = load damage exponent for the damage type
The standard load for different kinds of axles and tyres are given in Table 2-1.

**Table 2-1: Schematic of axle configuration and loads on axle groups that cause the same damage as a standard axle (Austroads, 2012)**

<table>
<thead>
<tr>
<th>Axle configuration</th>
<th>Single axle single tyre (SAST)</th>
<th>Single axle dual tyre (SADT)</th>
<th>Tandem axle single tyre (TAST)</th>
<th>Tandem axle dual tyre (TADT)</th>
<th>Triaxle dual tyre (TRDT)</th>
<th>Quad-axle dual tyre (QADT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Schematic</td>
<td><img src="image1.png" alt="Schematic" /></td>
<td><img src="image2.png" alt="Schematic" /></td>
<td><img src="image3.png" alt="Schematic" /></td>
<td><img src="image4.png" alt="Schematic" /></td>
<td><img src="image5.png" alt="Schematic" /></td>
<td><img src="image6.png" alt="Schematic" /></td>
</tr>
<tr>
<td>Axle group mass (kN)</td>
<td>53</td>
<td>80</td>
<td>90</td>
<td>135</td>
<td>181</td>
<td>221</td>
</tr>
<tr>
<td>Axle group mass (t)</td>
<td>5.41</td>
<td>8.16</td>
<td>9.18</td>
<td>13.76</td>
<td>18.46</td>
<td>22.6</td>
</tr>
</tbody>
</table>

During pavement design process, the value of load damage exponent varies based on the design methods, which can be divided into empirical design and mechanistic-empirical design. Pavement empirical design is applicable to new flexible pavements which are comprised of a thin bituminous surfacing (sprayed seal or asphalt less than 40mm thick) over granular material while the latter approach is suitable for new flexible pavements with one or more layers of bound material (asphalt or cemented material). The introduction of mechanistic-empirical design method improves the drawbacks of the former design guides as the features of materials and their failure mechanisms are considered. For granular pavements, only the overall pavement deterioration is taken into account. With regard to flexible pavements with one or more bounds, there are three types of distress should be calculated: (1) fatigue of asphalt; (2) rutting and loss of surface shape; (3) fatigue of cemented materials. The specific values of load damage exponent are determined in the following Table 2-2 (Austroads, 2008, Austroads, 2012).
Table 2-2: Load damage exponents for each specific type of damage (Austroads, 2008, Austroads, 2012)

<table>
<thead>
<tr>
<th>Design method</th>
<th>Pavement type</th>
<th>Type of damage</th>
<th>Load damage exponent (m)</th>
<th>Damage Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Empirical</td>
<td>Granular pavement with thin bituminous surfacing</td>
<td>Overall pavement damage</td>
<td>4</td>
<td>ESA</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fatigue of asphalt</td>
<td>5</td>
<td>SAR5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rutting and loss of surface shape</td>
<td>7</td>
<td>SAR7</td>
</tr>
<tr>
<td>Mechanistic</td>
<td>Pavement with one or more bound layers</td>
<td>Fatigue of cemented materials</td>
<td>12</td>
<td>SAR12</td>
</tr>
</tbody>
</table>

Therefore, the truck factor for a whole vehicle can be expressed as the sum of damage factor which is calculated by comparing the actual load and reference load for each axle group. Reference load is the same as standard load mentioned above. This definition is shown by Equation (2-2), a transformation of Equation (2-1):

\[
DF = \sum_{i=1}^{n} \left( \frac{\text{Actual load for axle group } i}{\text{Reference load for axle group } i} \right)^m
\]  

Where:

\(DF\) = damage factor, equivalent to truck factor

\(n\) = number of axle groups

\(m\) = load damage exponent
2.4 Pavement deterioration models

The prediction of pavement performance is necessary as it is relevant to many components in the pavement management system, such as pavement structural design, the determination of the years that rehabilitation is needed, maintaining the existing road network to a required service level and selecting the optimal cost-effective maintenance and rehabilitation alternatives (Amin, 2015).

The term, pavement performance, is a measure of the condition of in-service pavement. There are broad indicators for pavement performance, which is normally expressed in two ways:

- Structural performance measures: expressed in terms of observable distresses such as rutting, cracking, roughness, potholing and surface bleeding and ravelling.
- Functional performance indices: expressed in terms of pavement serviceability, which might be derived from the above distresses (i.e. composite measures). Present serviceability index (PSI), pavement condition rating (PCR) and international roughness index (IRI) are examples of functional measures (Saba et al., 2006, Austroads, 2009).

Normally, pavement performance prediction models can be divided into two categories-deterministic and stochastic models. The development concept, the formulation process as well as the output format are the three main differences between both types of prediction models (Li et al., 1996, Li et al., 1997, Amin, 2015).
2.4.1 Deterministic models

The deterministic models can be further separated into purely mechanistic models, mechanistic-empirical models and regression models (Li et al., 1996, Li et al., 1997). The mechanistic models depict the relationship between a response parameter, such as stress, strain and deflection (Li et al., 1997). Layered elastic and finite element methods are two common mechanistic models. There is no purely mechanistic model available currently because of the requirement of detailed structural information (Bai et al., 2010). The mechanistic-empirical models are a combination of mechanistic and empirical models. These models draw the relationship between a response parameter, such as roughness, cracking, and traffic loading or age (Li et al., 1997, Bai et al., 2010). Regression models (empirical models) are developed based on experimental or observed data, which link an observed pavement performance parameter with factors such as pavement thickness, age, traffic loading, pavement material or their combination. Mechanistic-empirical and regression models are widely used in practice (Li et al., 1997, Austroads, 2009, Bai et al., 2010).
Figure 2-5: Factors, and interactions, which can affect pavement performance
(Tighe et al., 2003)

Figure 2-5 indicates the factors which have effects on pavement performance while Figure 2-6 shows a representative pavement deterioration curve including the immediate effects of pavement maintenance and rehabilitation activities. Pavement deterioration phase (1) represents the increase of pavement distresses and therefore pavement condition decreases with time. Phase (2) is the immediate improvement of pavement condition due to pavement maintenance and rehabilitation activities. Phase (3) shows the trend of pavement deterioration with time after pavement treatments, which may vary with the trend of deterioration in phase (1) (Austroads, 2009).
A general equation of a deterministic pavement performance prediction model can be expressed as follows (Li et al., 1997):

\[
P_{CS_t} = f(P_0, ESA_t, H_e, SN, M_R, C, W, I)
\]

(2-3)

where:

- \(P_{CS_t}\) = generalized pavement condition state (PCS) at year \(t\), where \(t\) is equal to 0, 1, 2, ..., T
- \(P_0\) = initial pavement condition state
- \(ESA_t\) = accumulated equivalent single axle loads applications at age \(t\)
- \(H_e\) = total equivalent granular thickness of the pavement structure
- \(SN\) = structural number index of total pavement thickness
\( M_R \) = subgrade soil resilient modulus

\( C \) = set of construction effects

\( W \) = set of climatic or environmental effects

\( I \) = interaction effects of the preceding effects

The following content lists some typical deterministic pavement performance prediction models in the literature.

2.4.1.1 AASHTO flexible pavement design model

The AASHTO developed the PSI for flexible pavement, which might be the most widely used pavement design method worldwide (Abaza et al., 2001). In this performance model, it mainly relates the PSI with 18-kip ESA (equals to a single axle with dual tyres applying an axle load of 80 kN to the pavement) and other factors such as material characteristics, drainage and environment and the reliability of pavement performance. Equation (2-4) is the transformation of the original AASHTO pavement design model (AASHTO, 1993):

\[
\log_{10}(\Delta PSI) = 0.5682 + [0.4 + \frac{1.094}{(SN + 1)}][\log_{10} ESA_j - Z_r S_0] \\
-9.36 \times \log_{10}(SN + 1) - 2.32 \times \log_{10} + 7.87
\]  

(2-4)

where:

\( \Delta PSI = PSI_0 - PSI_t \), namely the difference between the initial design serviceability index (\( PSI_0 \)) and the serviceability index at year \( t \) (\( PSI_t \))
\[ Z_R \text{ and } S_0 = \text{standard normal deviate and combined standard error of the traffic prediction and performance prediction, respectively} \]

\[ M_R = \text{subgrade soil resilient modulus} \]

\[ ESA_t = \text{accumulated equivalent single axle loads applications at age } t \]

\[ SN = \text{structural number index of total pavement thickness} \]

2.4.1.2 A simplified pavement performance model

Lee et al. (1993) developed a simplified pavement performance prediction model. PSR is utilized to stand for the pavement surface condition, which is predicted based on factors such as pavement initial condition, structure number, cumulative traffic loading, pavement age as well as weather condition. The simplified performance model is shown as follows:

\[ PSR_t = PSR_i - AF \times a \times STR_t^b \times Age_t^c \times CESAt^d \] (2-5)

where:

\[ PSR_t = \text{pavement serviceability at year } t \]

\[ PSR_i = \text{initial value of } PSR \text{ after construction or major rehabilitation} \]

\[ a, b, c, d = \text{pavement performance coefficients dependent on the type of the pavement} \]

\[ AF = \text{adjustment factor relevant to the climate conditions} \]
$STR_t =$ structural number of the pavement at year $t$

$Age_t =$ age of the pavement at year $t$ after initial construction or a major rehabilitation

$CESA_t =$ Cumulative 80 kN equivalent single-axle loads applied to pavement in the heaviest traffic lane in year $t$, unit: millions

2.4.1.3 IRI Model

A mechanistic roughness model linking the pavement roughness with the number of load repetitions, axle load, and asphalt layer thickness was proposed by Saleh et al. (2000). It is found that the initial roughness is the most significant factor that contributes to future pavement roughness.

\[
IRI = -1.415 + 2.923 \sqrt{IRI_0} + 0.00129 \sqrt{ESA} + 0.000113 T - 5.485 \times 10^{-10} p^4 - 10^{-5} T \sqrt{ESA} + 5.777 \times 10^{-12} p^4 \sqrt{ESA} \tag{2-6}
\]

where:

$IRI =$ international roughness index, unit: m/km

$IRI_0 =$ initial IRI value, unit: m/km.

$ESA =$ number of load repetitions

$P =$ axle load, unit: kN

$T =$ asphalt concrete layer thickness, unit: mm
2.4.1.4 Traffic-Related Model

Smadi and Maze (1994) developed a performance model which only related the PCR with the 18-kip equivalent single-axle loads based on 10 years traffic data. The traffic-related equation is listed below:

\[ PCR = 100 - \alpha(CESA) \]  

(2-7)

where:

- \( CESA \) = cumulative 18-kip equivalent single-axle loads
- \( \alpha \) = a constant dependent on surface type.

2.4.2 Stochastic Models

Darter and Hudson (1973) highlighted the necessity of developing probabilistic pavement performance models for flexible pavement design. In the previous section, it is known that the deterministic pavement performance prediction model is a mathematical function that is derived from observed or measured pavement deterioration through mechanistic, mechanistic-empirical or regression approach (Li et al., 1996, Li et al., 1997, Abaza, 2004). The advantages of deterministic models are that they are easy to understand and particularly suitable for the circumstance of lack of actual pavement performance condition data. However, the predicted future pavement condition of this kind of models is a precise value which may be inaccurate as pavement performance is a stochastic process that varies with different factors. On the contrary, the stochastic pavement
performance predicted model takes the uncertainties into consideration, which is a probability function that predicts the future pavement state with a certain level of probability. The probabilistic outcomes of the future pavement conditions are obtained based on the professional engineering judgment or the analysis of the past pavement performances (Abaza, 2004). The formulation of stochastic models is normally more time-consuming and cumbersome than that of deterministic models.

Markov transition probability matrix is commonly applied by researchers to address the probabilistic property of future pavement condition (Abaza et al., 2004, Pittenger et al., 2012, Denysiuk et al., 2017, Mandiartha et al., 2017). A Markov chain process can be expressed as the probability of a pavement condition moving from one state to another state. The specific transition probability matrices for different types of pavement and maintenance activities undertaken are developed based on historical data. Figure 2-7 can be used to illustrate the fundamental difference between the deterministic and Markov probabilistic approaches. The deterministic approach predicts future pavement condition based on a representative value (i.e. mean value) whereas the Markov probabilistic approach considers the distribution of the pavement condition at a certain time point (Weninger-Vycudil et al., 2008).
Another approach to account for the stochastic nature of future pavement condition is to apply the probability distributions to represent the uncertain inputs (such as traffic loading, environment, pavement materials, etc.) in the deterministic deterioration model developed using regression analysis (Chootinan et al., 2006, Gao and Zhang, 2008, Chou and Le, 2011). Monte Carlo simulation method is considered to generate the random value of the inputs based on the statistical distributions. The advantage of this method is that the distribution of the outcome can be easily obtained through simulation, which avoids complicated mathematic formulations, that are often intractable (Takeshi, 2013).

2.5 Conclusion

This chapter mainly reviewed three parts: WIM technology, truck factor and pavement performance prediction models. It is shown that WIM systems can provide detailed truck
information and have broad applications in the literature, such as the study of WIM accuracy, infrastructure design and overloaded vehicles. However, from the author’s best knowledge, there has been limited research about the usage of WIM data in the assignment of freight to minimize pavement damage, thus indicating the research gap. Also, this chapter introduced the approach of quantifying the pavement damage caused by vehicles with different configurations and loads, which gave the fundamental knowledge for this study. Besides, the review of pavement performance prediction models assists in the understanding of the factors contributing to pavement deterioration as well as scheduling future pavement treatments.
3 DATA FILTER AND ANALYSIS

3.1 Introduction

Weigh-in-motion technology can provide various weight information about the trucks passing the monitor site without interrupting the traffic flow. In this chapter, the data of the freight vehicles recorded by one representative WIM site located in the M80 Western Ring Road in Melbourne is analysed. The chapter introduces the method applied to filter and classify the raw WIM data and investigates the fundamental characteristics of the truck fleet operating on the freeway, such as the proportions of vehicles falling into each type of trucks, the assignment of freight, the pavement damage caused by vehicle class and so on. The sections in this chapter are given in more details as follows:

- Section 3.2 provides the detailed introduction of the source of WIM data
- Section 3.3 lists the steps utilized to eliminate the unreliable vehicle records and how to classify the vehicles
- Section 3.4 introduces the method of quantifying the pavement damage caused by various vehicle configuration
- Section 3.5 explores the basic attributes of the vehicle fleet and the truck impact on pavement structure for the typical WIM site
- Section 3.6 is a summary of this chapter
3.2 Source of WIM data

The WIM data analysed for case study was provided by VicRoads for trucks traveling on each of the four lanes of the south bound carriageway on the M80 Western Ring Road (WRR) between Boundary Road and Deer Park By-Pass from 1st April 2013 to 30th April 2013. Figure 3-1 shows a close-up view of the location of WIM site on a google map. This road is a divided freeway located about 10 kilometres west of the central city area of Melbourne, which is a good representative for investigating the features of freight vehicles due to the daily high level of truck movements.

Figure 3-1: M80 Western Ring Road between Boundary Road and Deer Park By-Pass
The WIM data for this site was collected by the VIPERWIM system, an advanced high-speed weigh-in-motion system consisting of piezoelectric sensors and inductive loops. For each lane of the carriageway, the piezoelectric sensors installed before and after an inductive loop are embedded 10mm below the road surface which provides adequate space for the natural curvature of the pavement structure. The working mechanism behind the VIPERWIM system is not complicated. When each axle of a vehicle passes over the WIM site, the sensors are triggered and therefore the weight and vehicle speed can be calculated. The time difference between each sensor activation allows the axle spacing to be determined. Cables embedded within the pavement are utilized to connect the sensors to data storage and control equipment housed within a roadside cabinet (AppliedTraffic, 2013). The WIM site located in M80 Western Ring Road is given in Figure 3-2.

![Figure 3-2: M80 Western Ring Road WIM site](image)

The data files used for analysing the larger truck data was generated by WIMNet, which is Transmetric Traffic Server’s module to manage WIM data. WIMNet contains data
storage and quality control functions to help properly maintain a set of WIM monitoring devices and allow WIM data to be validated and calibrated (Thompson et al., 2016).

A variety of information of trucks is provided by WIMNet. The output of the data can be divided into two groups: measured information and estimated information. Measured information includes: site & lane, time, speed, vehicle class (Austroads vehicle class), the spacing and weight of axles as well as vehicle configuration (number of axles and axle groups, pattern of axle groups-axles in each axle group). Estimated information contains: GVM, tare weight, payload, legal limit weight, the weight of axle groups, and ESA calculated based on the recorded axle group loads, standard loads and the fourth power law. The tare weight and legal limit weights were assumed constant for vehicles having the same configuration (Ren et al., 2016).

3.3 Criteria applied for filtering WIM data

Appendix A describes the procedure of how to open the original WIM data files. According to Figure I, there are various types of vehicle information can be provided by WIM systems. The complete description of the abbreviations for each field in Figure I is listed in Appendix A as well (Table I).

Although the truck records were roughly managed by WIMNet, there was still a considerable percentage of WIM data discovered unreliable and containing errors. Also, the datasets were composed of records of different classes of vehicles and each record did not have the direct information about vehicle classification. The Austroads vehicle classification system given in Table 3-1 and the detailed information about the axle patterns by truck subclass illustrated in Appendix B were applied to classify the recorded trucks. In Table 3-1, there are criteria related to the distance between adjacent axles. Other
respects were also considered to help eliminate the unreliable vehicle readings due to mistakenly recorded by the WIM sensors.

**Table 3-1: AUSTROADS vehicle classification system (Austroads, 2008, Austroads, 2012)**

<table>
<thead>
<tr>
<th>Length (miles)</th>
<th>Type</th>
<th>Axle and Group</th>
<th>Vehicle Type</th>
<th>Typical Description</th>
<th>Class</th>
<th>Parameters</th>
<th>Typical Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short up to 5.3m</td>
<td>Short</td>
<td>1 or 2</td>
<td>Sedan, Wagon, 4WD, Utility, Light Van, Bicycle, Motorcycle, etc</td>
<td>(D_1 = 3.2m) and axles = 2</td>
<td>1</td>
<td>groups = 3</td>
<td>(D_1 = 2.7m) or (D_1 = 3.2m), (D_2 = 3.4m) and axles = 3 or 5</td>
</tr>
<tr>
<td>Medium 5.3m to 14.9m</td>
<td>3, 4 or 5</td>
<td>3</td>
<td>Trailer, Caravan, Boat, etc</td>
<td></td>
<td>2</td>
<td>groups = 3</td>
<td></td>
</tr>
<tr>
<td>Long 15.3m to 30.5m</td>
<td>2</td>
<td>2</td>
<td>Two Axle Truck or Bus</td>
<td>(D_1 = 3.2m) and axles = 2</td>
<td>3</td>
<td>axles &gt; 3 and groups = 2</td>
<td></td>
</tr>
<tr>
<td>Medium Combination 17.3m to 58.0m</td>
<td>3</td>
<td>2</td>
<td>Three Axle Truck or Bus</td>
<td>axles &gt; 3 and groups = 2</td>
<td>4</td>
<td>axles &gt; 3 and groups = 2</td>
<td></td>
</tr>
<tr>
<td>Long Combination &gt; 58.0m</td>
<td>1</td>
<td>2</td>
<td>Four Axle Truck</td>
<td></td>
<td>5</td>
<td>axles &gt; 3 and groups = 2</td>
<td></td>
</tr>
<tr>
<td>Medium Combination 17.3m to 58.0m</td>
<td>3</td>
<td>3</td>
<td>Three Axle Articulated</td>
<td>(D_1 = 3.2m) and axles = 3 and groups = 3</td>
<td>6</td>
<td>axles &gt; 3 and groups = 3</td>
<td></td>
</tr>
<tr>
<td>Long Combination &gt; 58.0m</td>
<td>4</td>
<td>2</td>
<td>Four Axle Articulated</td>
<td>(D_1 = 3.2m) or (D_1 = 2.9m) or (D_1 = 3.2m) and axles = 4 and groups = 2</td>
<td>7</td>
<td>axles &gt; 3 and groups = 2</td>
<td></td>
</tr>
<tr>
<td>Medium Combination 17.3m to 58.0m</td>
<td>5</td>
<td>2</td>
<td>Five Axle Articulated</td>
<td>(D_1 = 3.2m) or (D_1 = 2.9m) or (D_1 = 3.2m) and axles = 5 and groups = 2</td>
<td>8</td>
<td>axles &gt; 3 and groups = 2</td>
<td></td>
</tr>
<tr>
<td>Long Combination &gt; 58.0m</td>
<td>6</td>
<td>2</td>
<td>Six Axle Articulated</td>
<td>(D_1 = 3.2m) or (D_1 = 2.9m) or (D_1 = 3.2m) and axles = 6 and groups = 3</td>
<td>9</td>
<td>axles &gt; 3 and groups = 2</td>
<td></td>
</tr>
<tr>
<td>Medium Combination 17.3m to 58.0m</td>
<td>&gt; 1</td>
<td>4</td>
<td>B Double</td>
<td>(D_1 = 2.9m) or (D_1 = 3.2m) or (D_1 = 4.0m) and groups = 2</td>
<td>10</td>
<td>axles &gt; 3 and groups = 2</td>
<td></td>
</tr>
<tr>
<td>Large Combination &gt; 58.0m</td>
<td>&gt; 1</td>
<td>5 or 6</td>
<td>Double Road Train</td>
<td>(D_1 = 2.9m) or (D_1 = 3.2m) or (D_1 = 4.0m) and axles = 6</td>
<td>11</td>
<td>axles &gt; 3 and groups = 2</td>
<td></td>
</tr>
<tr>
<td>Large Combination &gt; 58.0m</td>
<td>&gt; 1</td>
<td>8</td>
<td>Triple Road Train</td>
<td>(D_1 = 2.9m) or (D_1 = 3.2m) or (D_1 = 4.0m) and axles = 6</td>
<td>12</td>
<td>axles &gt; 3 and groups = 2</td>
<td></td>
</tr>
</tbody>
</table>

The following is a filtering prototype that was utilized to screen the WIM data analysed in this study. Truck records that meet the following criteria were deleted:

- Record where vehicle belongs to class 1 and class 2 (light vehicles) as they have a negligible impact on pavement. Therefore, these two vehicle classes should be excluded in this study (Austroads, 2008, Austroads, 2012).
- Record where vehicle speed is greater than 120 km/h. For example, the extreme vehicle speed 307km/h is not considered to be reliable.
- Record where the number of the vehicle axles is less than two. Some ‘single axle’ patterns of trucks must be eliminated.
• Record where there is an abnormal truck axle pattern. For example, the axle configuration ‘3-1’ does not exist in real world.

• Record where GVM is less than 6.5 ton as the default value for minimum tare mass for any truck configuration is 6.5 ton.

• Record where GVM is 50% larger than the permissible weight limit. A proportion of overweight vehicles are remained as they do exist in real world. However, extremely heavy weight should be deleted. For example, GVM is 35.644 ton while the legal limit is 17.5 ton.

• Record where vehicle record contains ‘WIM code violation’. For instance, the code ‘134217728’ means sensor error record.

• Record where any axle weight is less than 1 ton. For example, the steer axle weight equals to 0.5 ton is too small and should be removed.

• Record where any adjacent axle spacing is larger than 2.1m in an axle group.

• Record where any axle spacing is less than 1m or larger than 10m.

3.4 Impact of heavy vehicles on pavement

To investigate the impact of heavy vehicles on road infrastructure, the term of Equivalent Standard Axles was applied to quantify the overall pavement damage. The number of ESA provided by WIMNet for each vehicle was estimated using the recorded weights and standard loads for axle groups based on the 4th power law developed in the United States in the 1950’s. Dual tires were assumed to be present on all axles but the steer axle. To calculate the ESA for each truck, the recorded weights for each axle group are divided by the standard loads for the corresponding axle group and raised by the power of 4 and
then summed together (Thompson et al., 2016). The standard axle loads for different axle-tyre combinations in Australia are illustrated in Table 2-1 mentioned in Chapter 2.

Equation (3-1) and (3-2) give examples of how to calculate the ESA for six-axle and nine-axle articulated trucks, also called as semi-trailers and B-doubles for simplicity. Semi-trailers belong to Class 9 Vehicles, which have three axle groups and axle pattern “1-2-3” representing a steer axle followed by a tandem axle group and then a triaxle group. B-doubles are Class 10 Vehicles with four axle groups and axle pattern “1-2-3-3” depicting a leading single axle followed by a twin axle group and then two triaxle groups. Figure 3-3 shows the typical configuration of semi-trailer and B-double.

Figure 3-3: Configuration of six-axle articulated trucks & nine-axle articulated axles (Ren et al., 2016)
Semi-trailers:

\[ ESA = \left( \frac{MoAG_1}{5.4} \right)^4 + \left( \frac{MoAG_2}{13.8} \right)^4 + \left( \frac{MoAG_3}{18.5} \right)^4 \]  

(3-1)

B-doubles:

\[ ESA = \left( \frac{MoAG_1}{5.4} \right)^4 + \left( \frac{MoAG_2}{13.8} \right)^4 + \left( \frac{MoAG_3}{18.5} \right)^4 + \left( \frac{MoAG_4}{18.5} \right)^4 \]  

(3-2)

Note: MoAG- Mass of Axle Group

3.5 Basic WIM data analysis

After applying the data filtering prototype mentioned above, there were 109,136 readings of trucks remained, including a few records of overloaded vehicles which do exist in the real life. Also, these truck records were further classified based on Austroads vehicle classification system and the table of vehicle subclasses. After this refinement, all the records were finally divided into nine vehicle classes, namely Class 3 to Class11. There were no records of road trains (Class 12 vehicles), which may be due to traffic restrictions in the urban areas. Table 3-2 gives the basic information of each lane. It is found that Lane 2 is the most heavily-trafficked lane compared to other lanes, which caused about 5.6×10^4 ESA to pavement. In addition, the amount of the total freight carried by 34,248 trucks in Lane 2 were approximately 3.36×10^5 tons.
Table 3-2: Vehicle information by lane

<table>
<thead>
<tr>
<th>Lane</th>
<th>Vehicle Number</th>
<th>Freight Amount (ton)</th>
<th>ESA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lane 1</td>
<td>32,450</td>
<td>302,028</td>
<td>50,580</td>
</tr>
<tr>
<td>Lane 2</td>
<td>34,248</td>
<td>336,192</td>
<td>56,184</td>
</tr>
<tr>
<td>Lane 3</td>
<td>28,298</td>
<td>278,101</td>
<td>43,652</td>
</tr>
<tr>
<td>Lane 4</td>
<td>14,140</td>
<td>173,934</td>
<td>26,950</td>
</tr>
<tr>
<td>Total Lanes</td>
<td>109,136</td>
<td>1090,255</td>
<td>177,366</td>
</tr>
</tbody>
</table>

Figure 3-4 to Figure 3-6 give an example of the proportion of vehicle number, freight as well as ESA carried by different types of trucks in Lane 2, the most heavily-trafficked lane. The pie charts of other lanes were not given out as they had the similar patterns with Lane 2. The share of vehicle number, freight and ESA by vehicle class for all lanes are illustrated in Figure 3-7 to Figure 3-9.

Figure 3-4: Percentage of vehicle number by truck classes for lane 2
Figure 3-5: Percentage of freight carried by different truck classes for lane 2

Figure 3-6: Percentage of ESA induced by different truck classes for lane 2
Figure 3-7: Percentage of vehicle number by class for all lanes

Figure 3-8: Percentage of freight carried by different truck classes for all lanes
With regard to vehicle number, two types of rigid truck (Class 3 & 4) and two articulated vehicle classes (Class 9 &10) were more common in this route in comparison to other types of vehicle either for Lane 2 or for all lanes. Also, Class 9 had the largest vehicle number. Although Vehicle Class 3 and 4 accounted for a considerable percentage of the total truck volume, they only carried a small part of the freight because of their small capacity. It is illustrated in Figure 3-5 and Figure 3-8 that about 80% of the total amount of freight were carried by Vehicle Class 9 and 10, thus representing a significant portion (close to 70%) in the total pavement damage (ESA) based on Figure 3-6 and Figure 3-9. According to Table II in Appendix B, there are many subclasses for Class 9 and Class 10. However, it can be seen in Figure 3-4 and Figure 3-7 that over 90% of Class 9 vehicles are six-axle articulated trucks (semi-trailers) while nearly 80% of Class 10 vehicles are nine-axle articulated vehicles (B-doubles). In addition, most of the freight task was undertaken by semi-trailers and B-doubles. Therefore, among all the subclasses, the largest percentage of the total ESA was induced by semi-trailers and B-doubles.
3.6 Summary

This chapter introduces the principles behind WIM system, lists the vehicle information provided by WIM technology as well as provides a filtering prototype used to eliminate the unreliable WIM records from M80 Western Ring Road. Also, the way about how to classify the vehicles in Australia was illustrated in detail. A preliminary study of the cleaned data was carried out to investigate the characteristics of the truck fleet. It was found that in the current Australian freight market, Class 9 and Class 10 vehicles were most widely used ones. Among all the subclasses for the two types of trucks, six-axle semi-trailers and nine-axle B-doubles transported most of the freight and thus they had a considerable impact on pavement. In the subsequent chapter, the payload distributions of semi-trailers and B-doubles as well as their induced pavement damage will be further studied. Mathematical models will be developed to minimize the total ESA.
4 Optimization of Payload Spectra for Semi-trailers and B-doubles

4.1 Introduction

In the previous chapter, it mainly introduced the procedure of tackling WIM data and some preliminary results were obtained based on the filtered data. It was found in Chapter 3 that six-axle semi-trailers and nine-axle B-doubles undertook the majority of freight and thus induced most of the pavement damage. Therefore, this chapter focuses on the two types of freight vehicles, semi-trailers and B-doubles, respectively. It explores the factors which have impacts on the total pavement damage. Also, the patterns of payload distributions for semi-trailers and B-doubles operating on the most heavy-duty lane are studied. This chapter also presents mathematical models developed to optimize the freight payload for the two most frequently used heavy vehicles (semi-trailers and B-doubles) affecting the pavement wear and tear. The optimisation models represent the main contribution of this research. The sections in this chapter are described as follows:

- Section 4.2 lists the basic statistics of semi-trailers and B-doubles operating on the most heavy-duty lane
- Section 4.3 identifies the major factors which influences the total ESA to formulate the mathematical model
- Section 4.4 explores the induced ESA values when semi-trailers and B-doubles carry various payloads
- Section 4.5 develops the mathematical models for optimizing the allocation of freight for trucks
Section 4.6 summarizes the whole chapter

4.2 WIM statistics about the most heavily-trafficked lane

The data utilized in this chapter is one-month of WIM data provided by VicRoads for trucks travelling on the most heavily-trafficked lane (i.e. Lane 2 mentioned in chapter 3) of the south bound carriageway on the M80 WRR between Boundary Rd and Deer Park By-Pass from 1st April 2013 to 30th April 2013. This is because only the most heavily-trafficked lane should be taken into consideration in the procedure of designing pavement and scheduling pavement maintenance and rehabilitation activities (Austroads, 2008, Austroads, 2012).

After filtering the data records carefully and classifying the trucks based on the Austroads vehicle classification system, it was found in Chapter 3 that most of one-month road freight task in terms of weight was carried by six-axle articulated trucks (semi-trailers) and nine-axle articulated trucks (B-doubles). In the scope of this study, only semi-trailers and B-doubles are considered. Besides their dominance in the freight transport, the choice of semi-trailers and B-doubles for optimisation simplifies the modelling and interpretation of results.

Also, to optimize the distribution of freight on the aspect of pavement damage, overloaded vehicles should be excluded as they break traffic regulations. Therefore, the data records belonging to semi-trailers and B-doubles should be re-filtered as overloaded vehicles are included in the previous chapter. The mass limits for these two vehicles are different. Currently, it exists two standards for mass limits in Australia, namely general mass limits and higher mass limits. The latter standard is applied for particular heavy vehicles, which have certified road friendly suspension and are accredited under the Mass
Management Module of the National Heavy Vehicle Accreditation Scheme (NHVAS) (NHVR, 2014). In this study, the higher mass limitation for both vehicle types was considered, which is illustrated in Table 4-1.

**Table 4-1: Limitation for semi-trailers and B-doubles (NHVR, 2016, VicRoads, 2004)**

<table>
<thead>
<tr>
<th></th>
<th>Higher Mass Limit (ton)</th>
<th>Length Limit (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Semi-trailers</td>
<td>45.5</td>
<td>19.0</td>
</tr>
<tr>
<td>B-Doubles</td>
<td>68.0</td>
<td>25.0</td>
</tr>
</tbody>
</table>

After eliminating the records of overloaded vehicles passing Lane 2, Table 4-2 lists the detailed attributes of the WIM recorded semi-trailers and B-doubles operating on the most heavy-duty carriageway. The freight capacity of B-doubles in terms of weight (46.6 tons) was substantially larger than that of semi-trailers (29.8 tons). It is also summarized that the one-month freight task undertaken by the two vehicle types was about $2.34 \times 10^5$ tons and the percentage of freight carried by more than 11,000 semi-trailers was 54% while the rest was undertaken by about 4,000 B-doubles. The number of ESA (overall pavement damage) for transporting the total freight was around $3.4 \times 10^4$, 58% of which was caused by semi-trailers. Although the average ESA of semi-trailers was much lower than that of B-doubles, the average payload carried by B-doubles was considerably higher.
Table 4-2: Basic statistics of one-month recorded data

<table>
<thead>
<tr>
<th></th>
<th>Semi-trailers</th>
<th>B-doubles</th>
<th>Sum</th>
</tr>
</thead>
<tbody>
<tr>
<td>GVM Legal Limit (ton)</td>
<td>45.5</td>
<td>68.0</td>
<td>/</td>
</tr>
<tr>
<td>Tare Mass (ton)</td>
<td>15.7</td>
<td>21.4</td>
<td>/</td>
</tr>
<tr>
<td>Maximum Freight Mass (ton)</td>
<td>29.8</td>
<td>46.6</td>
<td>/</td>
</tr>
<tr>
<td>Vehicle Number</td>
<td>11,212</td>
<td>4,175</td>
<td>15,387</td>
</tr>
<tr>
<td>Freight (ton)</td>
<td>126,313(54%)</td>
<td>107,366(46%)</td>
<td>233,679</td>
</tr>
<tr>
<td>ESA</td>
<td>19,757(58%)</td>
<td>14,291(42%)</td>
<td>34,048</td>
</tr>
<tr>
<td>Average Payload/truck (ton)</td>
<td>11.3</td>
<td>25.7</td>
<td>15.2</td>
</tr>
<tr>
<td>Average ESA/truck</td>
<td>1.8</td>
<td>3.4</td>
<td>2.2</td>
</tr>
</tbody>
</table>

As recorded, both vehicle classes carried various amounts of freight and the distributions of the payload carried by them are shown in Figure 4-1. The relative frequency of semi-trailers and B-doubles was calculated based on dividing the number of vehicles falling into each payload groups by the traffic volume. It is observed that the distributions tended to be bi-modal, representing the prevalence of either unloaded or almost fully loaded vehicles. The reason of the existence of these empty trucks might be that they were on the way back after completing their freight transport tasks. These empty trucks caused pavement wear and tear, however, have little contribution in freight transport. Besides, there was a considerable proportion of trucks only partially utilizing their weight capacity. This may be due to the limitation in the volume capacity of trucks or lack of organization in the allocation of freight.
4.3 Formulation of the problem

To transport a given amount of freight, there are five factors that have major impacts on the total ESA (pavement damage) induced by semi-trailers and B-doubles, which are listed in detail as follows:

- Total weight of freight (freight task);
- Number of semi-trailers and B-doubles;
- Percentage of freight carried by semi-trailers and B-doubles;
- Vehicle number at each payload bins/intervals (probability density function (PDF) of payloads) for semi-trailers and B-doubles;
- Payload-related ESA for semi-trailers and B-doubles;

This study investigates the sensitivity of the total ESA to the change of each of the previous factors and thus, how to optimize payload distributions for semi-trailers and B-doubles under fixed freight task to minimize the total ESA. The following mathematical model is derived to describe the variables and objective of the optimization function:
Objective function:

$$\min \ ESA = \sum_{i=1}^{m} p_i V_i E_s(x_i) + \sum_{j=1}^{n} p_j V_j E_b(x_j)$$  \hspace{1cm} (4-1)$$

Subject to:

$$x_i \in [0, l_i] \quad \forall i$$  \hspace{1cm} (4-2)$$

$$x_j \in [0, l_b] \quad \forall j$$  \hspace{1cm} (4-3)$$

$$\sum_{j=1}^{n} (p_j V_b) x_j = p_0 W \quad \forall p_0 \in [0, 1]$$  \hspace{1cm} (4-4)$$

$$\sum_{i=1}^{m} (p_i V_s) x_i = (1 - p_0) W \quad \forall p_0 \in [0, 1]$$  \hspace{1cm} (4-5)$$

Where:

$m$ ($n$): the total number of payload bins for semi-trailers (B-doubles);

$V_s$ ($V_b$): the total vehicle number of semi-trailers (B-doubles);

$p_i$ ($p_j$): the probability of semi-trailers (B-doubles) falling into payload bin $i$ ($j$);

$x_i$ ($x_j$): upper bound value at payload bin $i$ ($j$) for semi-trailers (B-doubles);

$E_s$ ($E_b$): payload-related ESA equation for semi-trailers (B-doubles);

$l_i$ ($l_b$): legal payload limit for semi-trailers (B-doubles);

$W$: the fixed total amount of freight required to be transported;
\( p_o \): the percentage of freight carried by B-doubles;

The objective function (4-1) contains two parts: the first is the total ESA of semi-trailers and the other is of B-doubles; Equations (4-2) and (4-3) gives the range of payload values; Equations (4-4) and (4-5) represent that the sum of the payload of each truck equals to the total amount of freight task and limits the percentage of freight undertaken by B-doubles.

Therefore, various variables should be considered to minimize the total ESA. Among them, two major ones are investigated in depth in the following sections (a) the payload-related ESA equations for the two types of trucks; (b) individual vehicle number at each payload bin.

4.4 Payload-related ESA module

The average ESA values were calculated using the WIM data. For simplicity, the vehicles were classified into several weight categories, averaging ESA within the groups. For example, vehicles with payload between 4.5 and 5.5 tonnes were grouped in the 5 tonnes category. A similar approach was adopted for other weight groups, then ESA were plotted against the weight (Figure 4-2). The standard deviations of each ESA were marked in the figure. It is illustrated that ESA grew exponentially when payload increased. Besides, the specific equations and their corresponding coefficients of determination (\( R^2 \)) were listed as well. At higher payload levels, B-doubles appeared to have significant advantages in ESA compared to semi-trailers undertaking the same amount of freight. With the satisfactory ESA-payload regression equations (high \( R^2 \) values), the ESA of either type of truck could be estimated based on the weight of freight it carries. Therefore, these equations in Figure 4-2 are used in Equation (4-1) for the purpose of optimization.
It can be seen from Equations (4-4) and (4-5) that the vehicle number of each truck type is a dependent variable related to the percentage of freight shared as well as the load spectra of the trucks. To study the effect of vehicle numbers at each payload bin on the total ESA, two different scenarios are considered and compared. One is that the payload of each vehicle is set to the same and the other is that the payloads for semi-trailers and B-doubles are assumed to follow the statistical distributions.

4.5.1 Optimization Scenario 1: Each vehicle carrying the same payload

Firstly, the simplest scenario was considered, that the payload for all the trucks were assumed to be constant and thus the number of vehicles will change to transport the required amount of freight. Under this circumstance, the objective function (4-1) can be rewritten as follows:
\[
ESA = (1 - p_o)W \frac{E(x_i)}{x_i} + p_o W \frac{E(x_j)}{x_j}
\]  

Therefore, to minimize the total ESA when carrying a fixed amount of freight, the ratios between ESA and payload are crucial parameters. In this study, payloads over ESA \(x_i / E(x_i)\) & \(x_j / E(x_j)\) is utilised to represent the efficiency of the trucks transporting the freight. \(x_i\) and \(x_j\) stand for the input (benefit), namely transporting the freight, whereas \(E(x_i)\) and \(E(x_j)\) represents the output (cost), namely induced pavement damage. The higher the efficiency is, the less ESA is caused while transporting the same weight of freight.

The vehicle efficiency against the various payloads carried by semi-trailers and B-doubles were drawn in Figure 4-3. It is shown that B-doubles were more efficient compared to semi-trailers when the loads were no less than 7 tons and the advantage of B-doubles rose with the increase of the weight of the freight, which was consistent with the results given in Figure 4-2. On the other hand, the optimum payload values for semi-trailers and B-doubles were found to be 13 tons and 19 tons (the peak of the two curves), respectively, rather than the highest capacity. Therefore, in terms of pavement protection, the most favourable payload for the trucks was less than half of the legal freight weight limit.
Figure 4-3: Trend of the efficiency of semi-trailers and B-doubles carrying various payloads

According to Equations (4-4) and (4-5), the changes in the percentage of freight carried by semi-trailers and B-doubles also had an influence on the total ESA. Therefore, the relationship between the Equation (4-6) calculated total ESA and different percentages of the total freight undertaken by B-doubles when both types of trucks carried the most efficient payloads (semi-trailers:13 tons, B-doubles:19 tons) was presented in Figure 4-4. The sensitivity of the total ESA to the percentage of freight transported by the type of trucks was also illustrated in Figure 4-4. As a comparison, the variation in total ESA when payload spectra followed the WIM recorded distribution (given in Figure 4-1) were given as well. It is shown that with the increase of the freight undertaken by B-doubles, the advantages in the total ESA under both conditions would increase linearly, corresponding to the trend shown in Equation (4-6). The minimum ESA would be obtained when the total freight was carried by B-doubles, which was decreased by 32.3% when applying
optimal payload points in comparison to the current ESA value following the WIM recorded distributions (see Figure 4-1). If the percentages of freight carried by the two types of trucks followed the WIM recorded values (semi-trailers: 54%, B-doubles: 46%), the total ESA can be reduced by 22.9%.

![Graph showing total ESA against different proportions of freight carried by B-doubles](image)

**Figure 4-4: Total ESA against different proportions of freight carried by B-doubles under the optimal payload points and WIM recorded payload distributions (Freight amount: \( W = 2.34 \times 10^5 \) tons)**

4.5.2 Sensitivity analysis of the variation of payload for total ESA

Although there was a significant decrease in total ESA when applying the most efficient payloads for semi-trailers and B-doubles, it is unrealistic that each semi-trailer and B-double carry the same amount of payload on every trip. Thus, a three-dimensional figure (Figure 4-5) was produced to compare the changes in the total ESA with various combinations of the payload for the two kinds of trucks. In Figure 4-5, the percentages of freight carried by semi-trailers and B-doubles are the same as the original WIM recorded distribution.
values. It is assumed that for each combination of payload, all semi-trailers and B-doubles carry the same payload, which varies between one to the legal limit. Then the ESA for each truck can be calculated based on the regression equations in Figure 4-2. When the total weight of freight and the percentage of freight carried by B-doubles are known, the required number of semi-trailers and B-doubles can be obtained for each combination of payload. Therefore, the value of the total ESA for each point on the pattern can be obtained based on the calculated vehicle number and the corresponding ESA for each truck. Table 4-3 helps to better understand how to calculate the total ESA for individual payload combination, which is used to derive Figure 4-5. The minimum total ESA among all the payload combinations was marked as a red dot in the pattern, which corresponded to the advantageous point given in Figure 4-3. A relatively optimum truck load combination area (the blue surface) was also given, which can be seen that the surface of the ESA in this area was flatter and lower compared to other areas. This means that the total ESA is not sensitive to the variations of payloads in a specific range. In other words, it may still have advantages in reducing the total ESA though the payloads for semi-trailers and B-doubles have some variations which means that not all the payloads stick to the most efficient values.
Table 4-3: Total ESA for individual payload combination (incomplete table)

<table>
<thead>
<tr>
<th>Payload/semi-trailer (ton)</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>160117</td>
<td>122759</td>
<td>110472</td>
<td>104485</td>
<td>100980</td>
<td>98762</td>
<td>97276</td>
<td>96255</td>
<td>95439</td>
<td>95071</td>
<td>94765</td>
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<td>54701</td>
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</tbody>
</table>

Figure 4-5: Total ESA against various truck payload combinations when the total freight amount and B-doubles’ freight share equal to WIM recorded statistics

\( W = 2.34 \times 10^5 \text{tons, } p_0 = 46\% \)
4.5.3 Optimization Scenario 2: Vehicles carrying different payloads

4.5.3.1 Fitted theoretical distributions

In this scenario, statistical distributions were utilized to fit the WIM recorded payload spectra for semi-trailers and B-doubles (Bi-modals in Figure 4-1) to investigate the probability of the vehicles falling into each payload interval. The reason for applying the theoretical distributions instead of using polynomials to fit the curve is that the latter one has little statistical meaning, even though higher $R^2$ values could be achieved. Also, compared to discrete probability function, statistical distributions are more straightforward and computationally efficient than tables of values. As the payload distributions for both types of trucks tended to be bi-modal, they were, therefore, decomposed into the sum of two theoretical distributions. This can be expressed by the following equation:

$$f = p_e f_1 + (1 - p_e) f_2$$

(4-7)

In this equation, $f_1$ and $f_2$ stand for the PDFs of the theoretical distributions. The proportions for the two distributions are $p_e$ and $1-p_e$, respectively. The final PDF of the whole bi-modal distribution is formed through adding the two distributions together, which is represented by $f$. Commonly used probability distributions are usually applied to fit the measured payload distributions. Figure 4-6 illustrates the approach of modelling axle load spectra with bi-modal mixture distributions.
In this study, the normal distribution is selected to model the second peak while lognormal distribution is chosen for the first peak to avoid the negative values. The PDF for normal and lognormal distributions are shown in Equations (4-8) and (4-9), respectively:

**Normal distribution PDF:**

\[
f_1(x; \mu_1, \sigma_1) = \frac{1}{\sigma_1 \sqrt{2\pi}} e^{-\frac{(x-\mu_1)^2}{2\sigma_1^2}}
\]  

**Lognormal distribution PDF:**

\[
f_2(x; \mu_e, \sigma_e) = \frac{1}{x \sigma_e \sqrt{2\pi}} e^{-\frac{(\ln x - \mu_e)^2}{2\sigma_e^2}}
\]

The method to determine the best-fitted statistical model is to substitute the PDF of the two distributions into Equation (4-7). Therefore, there are five unknowns \((p_1, \mu_e, \sigma_e, \mu_l, \sigma_l)\) in total in the final model, which can be obtained based on optimization and represented...
as decision variables. In this case, the objective was set to minimize the sum of the squares of the error (or maximize the $R^2$) between $f$ and the recorded freight pattern for semi-trailers and B-doubles. MATLAB Optimization Toolbox was used to solve these unknowns by giving the objective function and the constraints of the variables.

Figure 4-7 and Figure 4-8 are the results of the best-fitted statistical distributions for WIM recorded payload spectra for semi-trailers and B-doubles. The parameters of the theoretical distributions are presented in the legends of the patterns. The $R^2$ values of the two statistical distributions for semi-trailers and B-doubles are 0.92 and 0.80, respectively. In addition, Figure 4-7 and Figure 4-8 are separated into two parts by using a black dash line. Relatively unloaded trucks are considered at the left of the dash line and loaded to its right.

![Figure 4-7: Fitted statistical distributions for relative frequency of payload for semi-trailers](image)

Figure 4-7: Fitted statistical distributions for relative frequency of payload for semi-trailers
4.5.3.2 Impact of the proportions of relatively unloaded piece

It can be noticed that the relatively unloaded piece accounted for a considerable percentage for both semi-trailers and B-doubles, which also induced pavement damage with little contribution to freight transportation. The influence and sensitivity of the proportions of relatively unloaded trucks on the total ESA for both semi-trailers and B-doubles were investigated. To study the unloaded part, other factors should be remained constant, such as the total vehicle number, the percentage share of freight by each type of truck, the standard deviations of the payloads as well as the first peak position of payload distribution.

To keep the total amount of freight carried the same, the mean value of the normal distribution will vary as the proportions of the relatively empty part changes. The calculation of the mean value of the second normal distribution is given in Equations (4-10) and (4-11) for semi-trailers and B-doubles, respectively. The length of the payload,
$d$, is set to be 0.1, which was small enough to regard the area between $f_s(b)$ and each payload bin as a rectangle to simplify the calculation. Besides, the upper bounds of the proportions of empty runs are the WIM recorded values (semi-trailers: 69%, B-doubles: 40%) which represented the current level of freight movements on roads.

Second peak position calculation equations:

semi-trailer:
\[
\sum_{i=1}^{n} f_s(x_i; \mu_s, \mu_e, \sigma_e, \sigma_i) dx_i = (1 - p_0) W
\]

B-double:
\[
\sum_{j=1}^{n} f_b(x_j; \mu_b, \mu_e, \sigma_e, \sigma_j) dx_j = p_0 W
\]

Subject to:

\[
d = 0.1
\]
\[
W, p_0, V_s, V_b = \text{WIM recorded values}
\]
\[
\mu_e, \sigma_e, \sigma_j, \mu_i, \sigma_i = \text{parameters of fitted statistical distributions}
\]
\[
p_e \in [0; 0.1; 0.2; 0.3; 0.4; 0.5; 0.6]
\]
\[
p_e^i \in [0; 0.1; 0.2; 0.3; 0.4; ]
\]

Solve:

$\mu_i$ & $\mu_i$

Where:
\( d \): the length of the payload bin;

\( f_b(f_b) \): the probability density function of payload for semi-trailers (B-doubles);

\( \mu_e(\mu_e') \): the mean value of the relatively unloaded piece for semi-trailers (B-doubles);

\( \sigma_e(\sigma_e') \): the standard deviation of the relatively unloaded piece for semi-trailers (B-doubles);

\( \mu_l(\mu_l') \): the mean value of the relatively loaded piece for semi-trailers;

\( \sigma_l(\sigma_l') \): the standard deviation of the relatively loaded piece for semi-trailers (B-doubles);

\( p_e(p_e') \): the proportion of relatively unloaded piece for semi-trailers (B-doubles);

According to Equations (4-10) and (4-11), the average load of laden truck can be obtained. The results of the position of the second peak when the proportion of relatively unloaded vehicles varied are shown in Figure 4-9 and Figure 4-10, which also present the changes in the shape of payload distribution curves. The WIM recorded distributions are also included in the patterns as a comparison. It is illustrated that since the percentage of unloaded vehicles decreased, the original trucks with high amount of payload could carry less, thus the payloads for more trucks becoming closer to the optimum payload points as given in Figure 4-3. For example, when the percentage of relatively unladen semi-trailers went down to 0%, the deviation of the freight of the trucks became small. Also, most of the payloads for semi-trailers were between 8 to 16 tons, which fell into a high vehicle efficiency interval based on the blue curve in Figure 4-3.
Figure 4-9: The second peak position of payload distribution for semi-trailers

Figure 4-10: The second peak position of payload distribution for B-doubles

ESA calculation equations for Figure 4-11:

\[ ESA_x = \sum_{i=1}^{m} f_{xi}(x; \mu_x, \sigma_x, \mu_i, \sigma_i) dV_i E_x(x_i) \]  

(4-17)
Figure 4-11: The total ESA against the variations of the relatively unloaded piece for semi-trailers and B-doubles

Figure 4-11 illustrates the trend of the total ESA calculated based on Equations (4-17) and (4-18) against the percentage change of the relatively empty parts for semi-trailers and B-doubles. According to Figure 4-11, it shows how much pavement damage could be avoided if the proportion of empty trucks could be reduced. It can be concluded from the figure that the proportion of relatively empty vehicles had a considerable impact on the total pavement damage. Besides, the effect of the changes in the percentage of relatively empty B-doubles were larger than that of semi-trailers on pavement. Therefore, it would be meaningful if the decision makers could lower the percentage of empty trucks by resource integration and optimization.
4.5.3.3 Optimization model: case study

After studying the impact of the unloaded part on the total ESA, a mathematical model was developed to minimize the pavement damage by optimizing the payload distributions for semi-trailers and B-doubles. The percentages of relatively empty parts for semi-trailers and B-doubles are set to be 35% and 20% (half of the WIM recorded percentages) as a case study. Although these percentages are arbitrarily chosen, they reflect reality and acknowledge that in practice the empty runs cannot be completely eliminated. In the mathematical modelling, only the right-side distributions, loaded trucks, are optimized. To specify, the mean values for relatively loaded semi-trailers and B-doubles are the decision variables. The average load of the left-side lognormal distributions and the standard deviations for mixed distributions in the objective function are same as the values in Figure 4-7 and Figure 4-8.

Therefore, the previous objective function (4-1) has been changed to the following mathematical model (4-19): where the decision variables are $\mu_l$ and $\mu_{l'}$, represent the average loads for semi-trailers and B-doubles.

**Objective function:**

$$
\text{Min } ESA = \sum_{i=1}^{m} f_s(x_i; \mu_s, \mu_l, \mu_{l'}, \sigma_l, \sigma_{l'})dV_s E_s(x_i) + \sum_{j=1}^{n} f_b(x_j; \mu_b, \mu_{b'}, \sigma_b, \sigma_{b'})dV_b E_b(x_j) \quad (4-19)
$$

**Subject to:**

$$x_i \in [0, l_i] \quad \forall i \quad (4-20)$$

$$x_j \in [0, l_b] \quad \forall j \quad (4-21)$$
\begin{equation}
\sum_{j=1}^{n} f_j(x_j; p_e, \mu_e, \mu_i, \sigma_e, \sigma_i) dV_b x_j = p_0 W \quad (4-22)
\end{equation}

\begin{equation}
\sum_{i=1}^{m} f_i(x_i; p_e, \mu_e, \mu_i, \sigma_e, \sigma_i) dV_e x_i = (1 - p_0) W \quad (4-23)
\end{equation}

\begin{equation}
p_0 \in [0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1] \quad (4-24)
\end{equation}

\begin{equation}
p_e = 0.35 \quad (4-25)
\end{equation}

\begin{equation}
p_e' = 0.20 \quad (4-26)
\end{equation}

\begin{equation}
\mu_e, \sigma_e, \sigma_i, \mu_e', \sigma_e', \sigma_i' = \text{parameters of fitted statistical distributions} \quad (4-27)
\end{equation}

**Decision variables:**

\( \mu_i \) & \( \mu_i' \)

After running the optimization model, it was found that the value of the decision variables kept the same when changing the proportions of freight carried by B-doubles. This is because during optimization, the parameters of the most efficient payload spectra would remain the same (as given in Figure 4-12), which would not be influenced by the percentages of freight undertaken by B-doubles. The changes of the freight shares of the two vehicle types only had an influence on their individual vehicle volume (\( V_s \) & \( V_b \)). Their relationship was linear which also means that the optimized ESA would have a linear relationship with the proportion of B-doubles, consistent to the trend in Figure 4-12.

The optimization results of the mathematical model and the minimum ESA values when changing the percentage of freight carried by B-doubles were given in Figure 4-12. Similarly, the change in the total ESA under the WIM recorded payload distribution was
also plotted as a comparison. The minimum ESA would be also obtained when all the freight were carried by B-doubles, which was reduced by 27.2% when applying the optimal payload distribution compared to the current ESA state marked in the pattern. Also, when the freight share by the two truck classes followed the WIM recorded values (semi-trailers: 54%, B-doubles: 46%), the total ESA can be decreased by 15.8%.

![Graph showing total ESA against different percentages of freight carried by B-doubles](image)

**Figure 4-12**: Total ESA against different percentages of freight carried by B-doubles under the optimal payload distribution and WIM recorded payload distribution (Freight amount: \( W = 2.34 \times 10^5 \) tons)

Table 4-4 concludes the total ESA under different arrangements of freight for trucks in the previous sections. To specify, when the freight allocation follows the WIM recorded distributions, the ESA values against the shares of freight by vehicle class are derived from Figure 4-4. For trucks with the optimum load points (semi-trailers: 13 tons, B-doubles: 19 tons), the total ESA against the different percentages of freight task undertaken by B-doubles are summarized based on Figure 4-4 as well. The ESA values
for freight vehicles following the optimal load distributions with empty runs (the outcome of objective function (4-19)) are concluded from Figure 4-12.

**Table 4-4: Total ESA under different arrangements of freight for trucks**

<table>
<thead>
<tr>
<th>Share of Freight</th>
<th>WIM Recorded Load Distributions</th>
<th>Optimum Load Points</th>
<th>Optimal Load Distributions Semi (35%); Bd (20%)</th>
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<tr>
<td><strong>Semi</strong></td>
<td><strong>Bd</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100%</td>
<td>0%</td>
<td>36,550</td>
<td>28,952</td>
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<td>90%</td>
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<td>80%</td>
<td>20%</td>
<td>35,461</td>
<td>27,782</td>
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<td>70%</td>
<td>30%</td>
<td>34,916</td>
<td>27,197</td>
</tr>
<tr>
<td>60%</td>
<td>40%</td>
<td>34,371</td>
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</tr>
<tr>
<td>54%</td>
<td>46%</td>
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<tr>
<td>0%</td>
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</table>

Note: Semi: semi-trailers; Bd: B-doubles

According to Figure 4-12 and Table 4-4, it can be concluded that there was still significant advantage remaining in reducing the pavement damage when the percentage of empty trucks was decreased by 50% and the total freight task can be distributed around the optimum payload points. The optimized distributions indicate how much pavement damage could be avoided through a more judicious distribution of freight loads. Three representative ESA values highlighted in red in Table 4-4 will be applied in the next
chapter which will investigate the impact of changes in ESA on pavement maintenance and rehabilitation costs.

4.6 Summary

This chapter focused on the freight transportation of two popular types of trucks in Australia, semi-trailers and B-doubles. It discussed their vehicle efficiency in terms of pavement performance and investigated the benefits of a more judicious distribution of the freight task. Weigh-in-motion data, which can provide detailed weight information of the trucks, were used to study their effects and current payload spectra. The main findings are concluded as follows:

1. When carrying the same payload, B-doubles had more advantages in pavement damage at higher payload levels than semi-trailers;

2. The best vehicle efficiency took place when the weights of freight carried by semi-trailers and B-doubles were 13 tons and 19 tons, respectively, and the benefit of reducing the total ESA would increase with the growth of the percentage of freight carried by B-doubles;

3. To distribute the total freight more efficiently, mathematical models were developed to optimize the load spectra. The WIM recorded bi-modal distributions were fitted by two mixed distributions. It was discovered that when decreasing the proportion of empty trucks on road, the freight can be assigned more evenly (i.e. lower the mean payload value), thus reducing the total pavement damage. A case study was developed to get the optimum payload spectra, which shows that it still has significant improvements in pavement damage but have more flexibility in the allocation of freight compared to all vehicles carrying the same payload;
This chapter gives the decision makers an indication of the potential usage of WIM data resources and a prototype of how to assign the freight task for trucks more efficiently. Other factors can be included in the future to make the freight management more practical, such as considering vehicle operating costs, social costs and environmental costs, etc.
5 COST SAVINGS IN PAVEMENT MAINTENANCE ACTIVITIES

5.1 Introduction

Truck traffic is an important factor leading to pavement deterioration. Chapter 4 explored the major characteristics that would have effects on pavement damage with regards to two popular types of freight vehicles, namely six-axle semi-trailers and nine-axle articulated vehicles. The payload distributions of the two types of vehicles were investigated based on the WIM data. Mathematical models were developed to improve the payload distributions for freight vehicles, through which it was found that there were considerable advantages in decreasing the derived pavement damage (total ESA). In this chapter, the influence of the reduced ESA in pavement treatments is discussed. A typical pavement deterioration model for flexible pavements is applied to determine the activity timing for pavement repair. In addition, the costs savings in pavement maintenance or rehabilitation activities over its service life is calculated in this chapter. Each section is briefly described as follows:

- Section 5.2 provides a simplified pavement performance prediction model as a basis of the determination of future pavement treatment schedules
- Section 5.3 calculates the savings in pavement repair costs based on three ESA scenarios derived from different payload distribution models and shares of freight by B-doubles
- Section 5.4 is the summary of this chapter
5.2 Pavement performance model for flexible pavements

Generally, the types of pavements are divided into two streams: flexible pavements and rigid pavements. In this study, a typical flexible pavement structure is selected to explore the potential cost savings in pavement treatments. This is because of the studied WIM road section belonging to the flexible pavements category. Also, there are wider applications of flexible pavements for constructing highways and freeways than rigid pavements. Figure 5-1 illustrates a common structure of a flexible pavement, which is normally composed of multiple layers-surface course, base course, subbase course and subgrade. Each layer is constructed with different materials. Subgrade is the natural formation of the existing soils while subbase course is a layer of material beneath the base course, which is usually made up of treated subgrade. Base course is composed of a mixture of granular materials, such as sand, crushed stone, or crushed slag. The top wearing course is commonly a layer of asphalt.

![Figure 5-1: A typical flexible pavement structure](image_url)

It is critical to choose a proper pavement prediction model, which shows the trend of pavement condition affected by different factors as well as determines the right time for
pavement maintenance or rehabilitation activities. Based on the literature review in Chapter 2, there are various pavement deterioration models developed by different scholars. For this study, a simplified pavement deterioration model proposed by Lee et al. (1993) mentioned in the literature review is applied as a base to predict the condition of the pavement over its service life. As a deterministic model, this pavement performance prediction model is straightforward and mature, and thus have wide applications by different researchers, which for example, assisted Chootinan et al. (2006) and Batouli and Mostafavi (2014) in the development of pavement management systems.

In this model (Equation (5-1)), pavement initial condition ($PSR_i$), structure number ($STR_i$), cumulative traffic loading ($CESA_i$), pavement age ($Age_i$) as well as weather condition ($AF$) are the factors which have impacts on pavement deterioration. The functional performance index, $PSR_i$, is used to represent the pavement condition at year $t$. $PSR_i$ has the numerical scale between 0 to 5. 0 means that the pavement condition is extremely poor while 5 stands for a perfect pavement. The simplified pavement performance prediction model is shown as follows:

$$PSR_t = PSR_i - AF \times STR_i^b \times Age_t^c \times CESA_i^d$$  \hspace{1cm} (5-1)$$

where:

$PSR_t$ = pavement serviceability at year $t$

$PSR_i$ = initial value of $PSR$ after construction or major rehabilitation

$a,b,c,d$ = pavement performance coefficients dependent on the type of the pavement
AF = adjustment factor relevant to the climate conditions

STR_t = structural number of the pavement at year t

Age_t = age of the pavement at year t after initial construction or a major rehabilitation

CESA_t = Cumulative 80 kN equivalent single-axle loads applied to pavement in the heaviest traffic lane in year t, unit: millions.

At different levels of pavement conditions, the corresponding pavement treatment activities should be carried out to avoid the premature pavement failures and provide acceptable ride quality for road users. There are different pavement repair activities, which can be categorized as routine maintenance, preventive maintenance, minor maintenance and major rehabilitation. The specific treatment techniques include cold patch, crack seal, chip seal, slurry seal, overlay and so on (Johnson, 2000). Generally, routine, preventive and minor maintenance only have a little effect on the improvement of pavement condition whereas major rehabilitation has noticeable impacts (Rajagopal and George, 1991, Abaza and Abu-Eisheh, 2003, Chootinan et al., 2006). For the long-term pavement maintenance horizon, the selection of the types of treatments as well as the activity timing is critical for maximizing the pavement performance and minimizing the pavement repair costs (Chootinan et al., 2006). However, this study mainly focuses on the economic benefits of the reduced ESA resulting from the improved assignment of freight for heavy vehicles. Therefore, only one type of treatment-major rehabilitation, was considered so as to simplify the calculation and put an emphasis on the variable, CESAt. The major rehabilitation activity would be triggered when the predicted pavement performance, PSR, reaches the terminal serviceability. Also, the pavement state was assumed to be restored to the initial condition after the treatment. In other words, it is
5.3 Calculation of cost savings in pavement maintenance & rehabilitation activities

According to Equation (5-1), the cumulative traffic loading in year \( t \) \( (CESA_t) \) is an important factor for predicting the pavement performance, which is determined by the base year ESA and the compound yearly ESA growth rate, shown in Equation (5-2).

\[
CESA_t = ESA_i \times \frac{(1 + GR)^t - 1}{GR} \quad (5-2)
\]

where:

\( CESA_t \) = Cumulative 80 kN equivalent single-axle loads applied to pavement in the heaviest traffic lane in year \( t \), unit: millions

\( ESA_i \) = Initial annual ESA at base year for scenario \( i \), unit: millions

\( GR \) = Annual growth rate, unit: %

Table 5-1 lists the specific values of the variables for pavement performance model. The initial pavement state, \( PSR_i \), is set to be 4.5, which is a common value applied in practice (Lee et al., 1993, Chootinan et al., 2006, Batouli and Mostafavi, 2014). The values of the calibrated parameters, \( AF \), a, b, c, d, are dependent on the type of pavements and climate conditions. For this study, the pavement is defined as flexible and the climate zone for
Melbourne is selected as intermediate as well as no freeze. The specific values could be traced from Tables III and IV in Appendix C. The pavement structure number \( (STR_i) \) as well as the annual growth rate for truck traffic were presumed and considered to be constant over the pavement service life. To investigate the potential advantage of optimized ESA in pavement rehabilitation costs, two ESA scenarios from the optimal payload distributions were selected. One was obtained when 46% of the total freight task was carried by B-doubles while the other was from B-doubles transporting all the freight. The WIM recorded ESA value was also considered as a comparison. The source of the three ESA values can be found in Table 4-4 in chapter 4.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>PSR(_i)</td>
<td>4.5</td>
</tr>
<tr>
<td>AF</td>
<td>0.43</td>
</tr>
<tr>
<td>a</td>
<td>(10^{1.155})</td>
</tr>
<tr>
<td>b</td>
<td>-1.8720</td>
</tr>
<tr>
<td>c</td>
<td>0.3499</td>
</tr>
<tr>
<td>d</td>
<td>0.3385</td>
</tr>
<tr>
<td>STR(_i)</td>
<td>5</td>
</tr>
<tr>
<td>GR</td>
<td>3%</td>
</tr>
<tr>
<td>ESA Scenarios:</td>
<td>Values</td>
</tr>
<tr>
<td>ESA(_1)</td>
<td>34,048(\times)12</td>
</tr>
<tr>
<td>ESA(_2)</td>
<td>28,662(\times)12</td>
</tr>
<tr>
<td>ESA(_3)</td>
<td>24,776(\times)12</td>
</tr>
</tbody>
</table>

Note: ESA\(_1\) - WIM recorded distribution, B-doubles share: 46%
ESA\(_2\) - optimization distribution, B-doubles share: 46%
ESA\(_3\) - optimization distribution, B-doubles share: 100%
All the variables in Equations (5-1) and (5-2) were determined. Hence, the serviceability of the flexible pavement in each year (PSR) can be calculated based on the two equations. To draw the curve of pavement condition, the analysis period and the terminal serviceability index were set to be 50 years and 2.5, respectively. Major rehabilitation would be triggered when the PSR was close to 2.5 to guarantee the pavement condition always above an acceptable level. Hence, the timing and frequency of pavement treatments were obtained. The trends of pavement performance for different scenarios of ESA during the service life were shown in Figure 5-2 to Figure 5-4.

![Figure 5-2: Predicted pavement rehabilitation activities based on WIM recorded ESA (B-doubles share: 46%)](image)

**Figure 5-2: Predicted pavement rehabilitation activities based on WIM recorded ESA (B-doubles share: 46%)**
Figure 5-3: Predicted pavement rehabilitation activities based on optimal payload distribution ESA (B-doubles share: 46%)

Figure 5-4: Predicted pavement rehabilitation activities based on optimal payload distribution ESA (B-doubles share: 100%)
It can be concluded that after improving the payload spectra for trucks, within a 50 years’ period, the number of major rehabilitation activities required reduced from 3 to 2. Also, if larger percentage of freight was undertaken by B-doubles, it would have more advantages in pavement treatments, which was reflected by the salvage value at the end of pavement life. The definition of salvage value will be explained in the next section. Figure 5-5 was drawn in order to show the differences in pavement repair activities more clearly.

**Figure 5-5: Comparison of pavement rehabilitation schedules for different payload spectra and freight shares**

To quantify the pavement maintenance & rehabilitation (M&R) activities, it is not enough to only consider the costs of pavement treatment activities. The salvage value of each alternative could not be neglected, which usually represents the remaining life of the pavement at the end of analysis period (Walls III and Smith, 1998). To take Figure 5-2 as an example, a rehabilitation is required at year 49 that will extend the pavement’s life.
for another 9 years. This additional serviceable life must be accounted for in the pavement costs. Therefore, to compare the difference of the three rehabilitation schedules shown in Figure 5-5, both pavement rehabilitation costs and the remaining salvage value should be considered.

The present value (PV) determined through discounting all future project costs to the base year, normally the year of construction, is used for comparison. Thus, the entire project costs can be expressed as a present year cost. Alternatives are then compared by comparing these base year costs (Walls III and Smith, 1998). The equation for calculating the total pavement treatment costs over its service period is expressed as follows:

\[
PV = \sum_{i=1}^{n} M \left( \frac{1}{1+r} \right)^{t_j} - S \left( \frac{1}{1+r} \right)^{t_r}
\]  

(5.3)

where:

- \( PV \) = present value of all M&R costs
- \( M \) = cost of the individual M&R activity, unit: $
- \( r \) = discount rate
- \( n \) = the total number of M&R activities over the analysis period
- \( t_j \) = the number of years from the present to the jth M&R activity
- \( S \) = salvage value at the end of the analysis period, namely the pavement remaining life
According to Equation (5-3), the PV for the three different scenarios can be obtained. When the discount rate is assumed to be 10% as a case study, the result is listed in Table 5-2. The steps of how to calculate the PV are presented in Appendix D. By comparing the PV of the alternatives, it can be concluded that it would have a significant advantage in decreasing the pavement treatment costs through optimizing the allocation of freight. When the optimal payload distribution was applied, 20.15% of pavement repair costs could be saved if 46% of freight task was carried by B-doubles in comparison to costs based on WIM recorded ESA. Besides, when all the freight was transported by B-doubles, the benefit in the costs saving was greater, decreased by 29.52%.

### Table 5-2: Present value of the three pavement rehabilitation schedules (r=10%)

<table>
<thead>
<tr>
<th>ESA Scenario</th>
<th>Present Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.1826M</td>
</tr>
<tr>
<td>2</td>
<td>0.1458M (-20.15%)</td>
</tr>
<tr>
<td>3</td>
<td>0.1287M (-29.52%)</td>
</tr>
</tbody>
</table>

#### 5.4 Summary

This chapter conducted a simple case study for the potential benefits of the optimized payload spectra in economic savings in pavement treatments. A typical flexible pavement structure was considered, and a simplified pavement performance prediction model was applied to perform a long-term pavement M&R strategy. Only the major rehabilitation activity was considered to simplify the calculation and put an emphasis on one factor, the initial annual traffic loading. It was discovered that through optimization of the payload
spectra, the number of the rehabilitation activities over the analysis period would be reduced compared to that of the WIM recorded distribution. Also, the benefits would be greater with the increase of the proportion of freight carried by B-doubles. In addition, the term of present value comprising M&R costs and salvage value was considered to quantify the long-term pavement treatments. The result indicates that there would be significant benefits in reducing the pavement maintenance costs if the distribution of freight transported by trucks could be optimized based on the mathematical prototype provided by the previous chapter. Therefore, the outcome of this chapter suggests that reducing empty runs and improving the payload distributions across heavy vehicles have important practical implications for pavement rehabilitation schedules.
6 CONCLUSION

6.1 Interpretation of results

This research mainly focused on the development of a mathematical model to optimize the distribution of freight in terms of pavement performance based on WIM data. The primary objectives mentioned in Chapter 1, have been achieved and the major findings are presented in this section. A summary of the main results is outlined below:

- A comprehensive literature review about WIM technology has been done. It was discovered that there have been wide applications of WIM systems in the literature. However, limited studies have focused on the usage of WIM data in the arrangement of freight for trucks.

- A filtering prototype for WIM database was developed to help delete the unreliable vehicle records, thus increasing the accuracy of further analysis and study.

- After analysing the WIM data of truck traffic operating on a representative freeway in Melbourne, it was found that in current Australian trucking market, six-axle semi-trailers and nine-axle B-doubles have undertaken the majority of the freight and thus accounted for a considerable proportion of the total pavement damage.

- Due to the popularity of semi-trailers and B-doubles, their impacts on the pavement structure are mainly investigated. It was discovered that when carrying the same weight of payload, B-doubles led to less pavement damage than semi-trailers. Besides, the advantages became greater at the higher payload levels.
The most efficient pavement performance took place when the freight transported by semi-trailers and B-doubles were 13 and 19 tonnes, respectively. In addition, the total ESA would decrease with the growth of the percentage of freight carried by B-doubles.

Mathematical models including all the factors which have impacts on pavement damage are developed. According to the case study, it is shown that it would have benefits in reducing the total ESA through decreasing the empty trucks, optimizing the payload spectra as well as increasing the amount of freight carried by B-doubles. This provides a prototype of how to make a more judicious distribution of freight.

Lastly, the potential benefits of the optimized spectra in cost savings in pavement M&R activities are investigated. Through the case study, it is shown that the pavement treatment costs over its analysis period would be significantly reduced by optimizing the allocation of freight transported on road.

6.1.1 Potential applications

It is expected that this study may help

- manage the WIM records by providing a filtering prototype, thus improving the accuracy of the database.
- promote the installation of more WIM sites as this technology can provide various useful vehicle information and assist in optimizing the freight movements.
- vehicle designers in the development of more productive heavy vehicles which will cause less damage on pavement.
• policy makers to develop a better toll charge system as the gap between the pavement damage caused by different configurations of trucks with various payloads is significant.

• freight transport industry to assign the freight movement for an important road section efficiently by providing a prototype optimization model, which may also assist in the development of models aiming at a network level.

6.2 Limitations for this study

Regarding this research, there are some limitations which are listed below:

• Only vehicle information from one representative WIM site located in one freeway in Melbourne is investigated. Also, the WIM data analysed in this study is one month-long and obtained in 2013, which means that they are not most up-to-date. This is mainly because of the availability of the data.

• In Australian vehicle classification system, there are multiple types of heavy vehicles, 10 classes and 52 subclasses in total. However, only two popular configurations of freight vehicles are discussed as they have played a dominant role in the current Australian freight transport market.

• To improve the allocation of freight transported by trucks, only the impact of their payload on pavement structure was considered. Other factors, such as vehicle operating costs and social costs, are not in the scope of this study.

• The optimization of the allocation of freight only aims at a specific road section. The freight trips for the whole road network are not considered, which indicates that the study is limited at the project level.
6.3 Recommendations for future work

Based on the limitations, future work can be expanded in different aspects. Firstly, the more latest WIM data from various sites can be investigated. Another is that the mathematical model for optimizing the distribution of freight can be enhanced, such as considering more types of vehicles and other constraints including vehicle operating costs, environmental costs and so on. Moreover, freight vehicles operating on a road network can be studied to extend the problem to the network level. With these effort, it will make this research more practical.
REFERENCES

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Alavi, S., Mactutis, J., Gibson, S., Papagiannakis, A. & Reynaud, D. (2001) Performance Evaluation of Piezoelectric Weigh-In-Motion Sensors under Controlled Field-
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Bureau of Infrastructure, Transport and Regional Economics (BITRE), 2011a, *Public Road-Related Expenditure and Revenue in Australia*, Information Sheet 40, BITRE, Canberra, ACT.


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APPENDIX A

To process the WIM data, the first step was to open the original data files in Microsoft Excel comma separated values format (.csv) which lost some features of the cells with Notepad and saved them as text format (.txt). Then the documents were loaded into Microsoft Excel sheets and finally saved as Excel Workbook (.xlsx) format to ensure all the features displayed so as to support further filtering and analysing. Figure I gives an example of the process of changing data format. The complete description of the abbreviations for each field in Figure I is listed in Table I.
Figure I: Process of changing the formats of WIM data files: (a) from '.csv' to '.txt'
(b) from '.txt' to '.xlsx'
### Table I: WIMNet data dictionary

<table>
<thead>
<tr>
<th>Field</th>
<th>Description</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOCID</td>
<td>Location ID</td>
<td>396</td>
</tr>
<tr>
<td>LANE</td>
<td>Lane Number</td>
<td>1</td>
</tr>
<tr>
<td>VEHID</td>
<td>Vehicle ID</td>
<td>164153880</td>
</tr>
<tr>
<td>DATE</td>
<td>Date of Vehicle Passing the Site</td>
<td>20130405</td>
</tr>
<tr>
<td>TIME</td>
<td>Time of Vehicle Passing the Site</td>
<td>6:20:33 AM</td>
</tr>
<tr>
<td>SPEED</td>
<td>Vehicle Speed(km/h)</td>
<td>78</td>
</tr>
<tr>
<td>NAXLES</td>
<td>Number of Axles</td>
<td>6</td>
</tr>
<tr>
<td>NGRPS</td>
<td>Number of Axle Groups</td>
<td>3</td>
</tr>
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<td>PATTERN</td>
<td>Vehicle Axle Pattern</td>
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</tr>
<tr>
<td>VEHCLASS</td>
<td>Vehicle Class</td>
<td>- not provided</td>
</tr>
<tr>
<td>GVM</td>
<td>Gross Vehicle Mass (ton)</td>
<td>35.345</td>
</tr>
<tr>
<td>TARE</td>
<td>Vehicle Tare Mass (ton)</td>
<td>15.7</td>
</tr>
<tr>
<td>FREIGHT</td>
<td>Freight Mass or Payload (ton)</td>
<td>19.645</td>
</tr>
<tr>
<td>ESA</td>
<td>Equivalent Standard Axles</td>
<td>2.861</td>
</tr>
<tr>
<td>LEGAL</td>
<td>Legal Mass of Vehicle (ton)</td>
<td>47.75</td>
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<td>Not Applicable</td>
<td>\</td>
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<td>LENGTH</td>
<td>Vehicle Length-not provided</td>
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<td>VEHCLASS 2</td>
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</tr>
<tr>
<td>TAG</td>
<td>Outlier Tag-user defined</td>
<td>0</td>
</tr>
<tr>
<td>CODE</td>
<td>Equipment Vender Error Codes</td>
<td>131072</td>
</tr>
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<td>AXLE_OVERFLOW</td>
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<td>\</td>
</tr>
<tr>
<td>GROUP_OVERFLOW</td>
<td>Not Applicable</td>
<td>\</td>
</tr>
<tr>
<td>A1(A2, ..., A16)_MASS</td>
<td>The Weight of Axle 1(2, ...,16)</td>
<td>5.742</td>
</tr>
<tr>
<td>A1(A2, ..., A16)_SPACE</td>
<td>The Space between Adjacent Axles (meter)</td>
<td>4.49</td>
</tr>
<tr>
<td>G1(G2, ..., G8)_MASS</td>
<td>The Weight of Axle Group 1(2, ...,8) (ton)</td>
<td>5.742</td>
</tr>
<tr>
<td>G1(G2, ..., G8)_TYPE</td>
<td>Axle Group type (first digit number of axles; second digit: 1-single tyre,2-dual tires; third digit: 0-steer axle, 1-not steer axle</td>
<td>110</td>
</tr>
</tbody>
</table>
## APPENDIX B

### Table II: Axle patterns by vehicle subclass

<table>
<thead>
<tr>
<th>Vehicle Class</th>
<th>Vehicle Subclass</th>
<th>Vehicle Axle Pattern</th>
</tr>
</thead>
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<td>3</td>
<td>31</td>
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<td>2-3</td>
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</tr>
<tr>
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<td>Vehicle Class</td>
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<td>129</td>
<td>1-2-2-3-2-3-2-3</td>
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</table>
APPENDIX C

Table III: Pavement performance coefficients based on the types of the pavement

(Lee et al., 1993)

<table>
<thead>
<tr>
<th></th>
<th>FLEX</th>
<th>COMP</th>
<th>JPCP</th>
<th>JRCP</th>
<th>CRCP</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\log_{10}a$</td>
<td>1.1550</td>
<td>-0.4185</td>
<td>0.5104</td>
<td>1.7241</td>
<td>0.7900</td>
</tr>
<tr>
<td>$b$</td>
<td>-1.8720</td>
<td>-0.1458</td>
<td>-1.7701</td>
<td>-2.7359</td>
<td>-1.3121</td>
</tr>
<tr>
<td>$c$</td>
<td>0.3499</td>
<td>0.5732</td>
<td>1.0713</td>
<td>0.3800</td>
<td>0.1849</td>
</tr>
<tr>
<td>$d$</td>
<td>0.3385</td>
<td>0.1431</td>
<td>0.2493</td>
<td>0.6212</td>
<td>0.2634</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.52</td>
<td>0.58</td>
<td>0.79</td>
<td>0.57</td>
<td>0.37</td>
</tr>
<tr>
<td>SEE</td>
<td>0.45</td>
<td>0.38</td>
<td>0.26</td>
<td>0.40</td>
<td>0.31</td>
</tr>
<tr>
<td>$N$</td>
<td>522 (31)</td>
<td>509 (0)</td>
<td>117 (3)</td>
<td>254 (21)</td>
<td>1204 (65)</td>
</tr>
</tbody>
</table>
Table IV: Recommended mean adjustment factors for different pavement types and climate zones (Lee et al., 1993)

<table>
<thead>
<tr>
<th>ZONE</th>
<th>FLEX</th>
<th>COMP</th>
<th>JPCP</th>
<th>JRCP</th>
<th>CRCP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wet; Freeze</td>
<td>0.59</td>
<td>0.81</td>
<td>1.04</td>
<td>1.11</td>
<td>0.56</td>
</tr>
<tr>
<td>Wet; Freeze-Thaw</td>
<td>0.40</td>
<td>0.85</td>
<td>1.13</td>
<td>1.07</td>
<td>0.40</td>
</tr>
<tr>
<td>Wet; No Freeze</td>
<td>0.44</td>
<td>0.69</td>
<td>0.78</td>
<td>0.40</td>
<td>0.60</td>
</tr>
<tr>
<td>Intermediate; Freeze</td>
<td>0.40</td>
<td>0.49</td>
<td>0.55</td>
<td>1.15</td>
<td>0.46</td>
</tr>
<tr>
<td>Intermediate; Freeze-Thaw</td>
<td>0.52</td>
<td>0.71</td>
<td>0.40</td>
<td>0.64</td>
<td>0.66</td>
</tr>
<tr>
<td>Intermediate; No Freeze</td>
<td>0.43</td>
<td>0.65</td>
<td>0.71</td>
<td>0.87</td>
<td>0.40</td>
</tr>
<tr>
<td>Dry; Freeze</td>
<td>0.40</td>
<td>0.63</td>
<td>0.76</td>
<td>1.50</td>
<td>0.79</td>
</tr>
<tr>
<td>Dry; Freeze-Thaw</td>
<td>0.40</td>
<td>0.40</td>
<td>0.40</td>
<td>0.40</td>
<td>1.50</td>
</tr>
<tr>
<td>Dry; No Freeze</td>
<td>0.40</td>
<td>0.79</td>
<td>0.40</td>
<td>0.40</td>
<td>0.40</td>
</tr>
</tbody>
</table>
APPENDIX D

Parameters:

Cost of the individual M&R activity: $ M$

Discount rate: 10%

Total number of M&R activities over the analysis period: 3 (ESA Scenario 1)

2 (ESA Scenario 2)

2 (ESA Scenario 3)

The year of the M&R activities: 20, 36, 49 (ESA Scenario 1)

22, 39 (ESA Scenario 2)

23, 41 (ESA Scenario 3)

The pavement remaining life at the end of the analysis period: 10 (ESA Scenario 1)

2 (ESA Scenario 2)

5 (ESA Scenario 3)

Length of the analysis period: 50 years

The equation for calculating the pavement treatment costs is:

\[ PV = \sum_{i=1}^{n} M \left( \frac{1}{1+r} \right)^i - S \left( \frac{1}{1+r} \right)^T \]

where:
PV = present value of all M&R costs

M = cost of the individual M&R activity, unit: $

r = discount rate

n = the total number of M&R activities over the analysis period

tj = the number of years from the present to the jth M&R activity

S = salvage value at the end of the analysis period, namely the pavement remaining life

T = length of the analysis period in years

Hence:

For ESA Scenario 1,

\[
PV = \left(\frac{1}{1+0.1}\right)^{20}M + \left(\frac{1}{1+0.1}\right)^{36}M + \left(\frac{1}{1+0.1}\right)^{49}M - \left(\frac{1}{1+0.1}\right)^{50} \times \frac{10}{10+(50-49)}M
\]

\[= 0.1826 M\]

For ESA Scenario 2,

\[
PV = \left(\frac{1}{1+0.1}\right)^{22}M + \left(\frac{1}{1+0.1}\right)^{39}M - \left(\frac{1}{1+0.1}\right)^{50} \times \frac{2}{2+(50-39)}M
\]

\[= 0.1458 M\]

For ESA Scenario 3,

\[
PV = \left(\frac{1}{1+0.1}\right)^{23}M + \left(\frac{1}{1+0.1}\right)^{41}M - \left(\frac{1}{1+0.1}\right)^{50} \times \frac{5}{5+(50-41)}M
\]

\[= 0.1287 M\]
Title:
Investigating the benefits of considering the payload spectra of freight vehicles on pavement costs based on weigh-in-motion data

Date:
2017

Persistent Link:
http://hdl.handle.net/11343/214437

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