Determining the Optimum Toll Levels for Freight Vehicles in Urban Conditions

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Declaration of Authorship

I, Hewage Loshaka Kumara Perera, declare that this thesis titled, 'Determining the Optimum Toll Levels for Freight Vehicles in Urban Conditions' and the work presented in it are my own. I confirm that:

I. The thesis comprises only my original work towards the PhD,
II. Due acknowledgement has been made in the text to all other material used,
III. The thesis is less than 100,000 words in length, exclusive of tables, maps, bibliographies and appendices

Hewage Loshaka Kumara Perera

Melbourne, May 2019
Abstract

Road pricing has been a very common practice in the world for many decades. Tolls are charged from road users as a tool to control traffic (congestion) or to raise finance (to recover capital and maintenance cost) or to control emissions. Public-Private Partnerships (PPP) or Build-Operate-Transfer (BOT) schemes have become common sources of financing infrastructure projects in many countries and tolls are collected to recover the cost. Private investors are attracted to such investments due to the potential opportunity to make high returns. On the contrary, the public has accepted private investments due to its transparency and rapid nature of construction compared with government authorities. However, in the operational stage, the public is more concerned about factors such as air quality, safety, and noise whereas investors are mostly concerned about the return on investment, which are in conflict. Nevertheless, toll levels appear to be set for maximizing profits ignoring many public concerns and other related issues.

Road prices are charged usually to recover pavement damage costs, road maintenance costs, capital costs, congestion costs, marginal savings, and emission costs. Regardless of the intended objective of charging vehicles on road, many studies in the past have looked at how various road pricing policies would change the behaviour of car traffic. But limited studies have been carried out identifying its impacts towards freight user behaviour. Demand for freight movement is increasing day to day as populations’ increase, especially in urban cities, which makes them significant. There were only a few studies carried out in the past to study the behaviour of freight vehicles, especially how they respond to toll charges. It was found that toll avoiding nature of freight vehicles increases the social and environmental costs.

City logistics is a concept which looks at total optimisation of freight movement in city limits. City logistics consider system optimisation not limited to economic aspects, but
also social and environmental. Freight vehicles are known to produce more externalities compared to cars, especially in city limits, where average speeds are low and most congested. As a result, freight vehicles in urban conditions produce more externalities such as crashes, noise, emissions, and it was found that conditions are getting worst due to toll avoiding nature of freight movement.

Determining optimum toll charges for freight vehicles are crucial decisions for policymakers considering socio-economic aspects. Therefore, the objective of this study is to develop a mathematical approach to design an optimal toll scheme for multi-class vehicles, considering direct costs and externalities. A bi-level modeling approach is used, where toll prices for multi-class vehicles are decided in the upper level and user response to toll charges are predicted using user equilibrium (UE) conditions with multi-class traffic assignment in the lower level.

In the upper level of the model development total cost calculation is an important component and thus a freight cost model was developed for Australia. For the cost model, local data were used when possible and gaps were filled from literature. In the lower level, the response to toll charges was embedded to user equilibrium conditions. A discrete choice experiment was carried out to find out how freight vehicles would respond to toll charges in Melbourne. This NP-hard, non-convex problem with non-linear constraints was solved using multi-objective optimisation. A Non-dominated sorting genetic algorithm was used for optimisation.

The model is applied to a small hypothetical road network and a real network in Melbourne with static demand conditions. Several applications of the model were performed considering various stakeholder objectives and optimal solutions were identified for enhancing City Logistics.

As an application, an effective toll charging scheme to minimize total network vehicular emissions while maintaining reasonable revenue for investors was found using the bi-level modeling approach. The model takes into consideration both toll revenue and total vehicle operating costs to produce an acceptable solution for both investors and road users. All major components of hazardous emissions (CO₂, PM2.5, SO₂ and NOₓ) were considered and estimated using an emission costs model developed based on secondary
data quantifying their impact on human health and the environment. Application of the model was illustrated using two networks mentioned above. Since this is a single objective optimisation, genetic algorithm was used to find near-optimal solutions for each toll-charging scenario. The results revealed that commonly used toll schemes are inefficient with respect to multi-stakeholder objectives. The toll charging scheme optimized using the GA was able to reduce the total emission cost of the network by 12% compared to a toll scheme currently used by a toll facility in a real network in Melbourne, Australia.

In the next section of this study, the toll problem is viewed from a different angle. As mentioned before toll roads constructed under public-private-partnerships (PPP) is very common around the world and due to the high capital cost invested and high risks associated with subsequent returns, investors are extremely concerned about future returns. As a result, the present trend is to charge high tolls for freight vehicles, especially in urban areas, which has created many problems as mentioned above. Considering the overall impacts, this section of the study identifies a tolling scheme with subsidies as the best option to minimize the total cost of urban freight transport which can lead to more sustainable city logistics in the future. A step by step process is followed in this study with illustrations to explore the best toll charging scheme considering various toll scenarios within a multi-objective framework.

Acceptability of toll schemes found in this study by multi-stakeholders is a critical decisive factor determining successful implementation of toll schemes. Multi-Agent Multi-Criteria Analysis was used to evaluate the various toll schemes produced from this study under various conditions. Surveys were carried out to collect the required information to feed the MAMCA. Finally, the best toll alternatives are ranked based on MAMCA outcome which can be used by policy decision makers considering the given conditions.
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Loshaka Perera, May 2019
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<tr>
<td>AADT</td>
<td>Average Annual Daily Traffic</td>
</tr>
<tr>
<td>AC</td>
<td>Accident Cost</td>
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<tr>
<td>AHP</td>
<td>Analytic Hierarchical Process</td>
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<tr>
<td>B/C</td>
<td>Benefit Cost ratio</td>
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<tr>
<td>IC</td>
<td>Infrastructure Cost</td>
</tr>
<tr>
<td>IRR</td>
<td>Internal Rate of Return</td>
</tr>
<tr>
<td>LCV</td>
<td>Light Commercial Vehicles</td>
</tr>
<tr>
<td>LL</td>
<td>Lower Level</td>
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<tr>
<td>MAMCA</td>
<td>Multi-Agent Multi-Criteria Analysis</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Full Form</td>
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<tr>
<td>--------------</td>
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<tr>
<td>MCDA</td>
<td>Multi Criteria Decision Analysis</td>
</tr>
<tr>
<td>MOOP</td>
<td>Multi Objective Optimisation Problem</td>
</tr>
<tr>
<td>MPEC</td>
<td>Mathematical Programming with Equilibrium Constraints</td>
</tr>
<tr>
<td>NC</td>
<td>Noise Cost</td>
</tr>
<tr>
<td>NOx</td>
<td>Nitrogen Oxide</td>
</tr>
<tr>
<td>NP hard</td>
<td>Non-deterministic Polynomial-time hardness</td>
</tr>
<tr>
<td>NPTR</td>
<td>Net Present Toll Revenue</td>
</tr>
<tr>
<td>NPV</td>
<td>Net Present Value</td>
</tr>
<tr>
<td>NSGA II</td>
<td>Non-dominated Sorting Genetic Algorithm- II</td>
</tr>
<tr>
<td>OD</td>
<td>Origin-Destination</td>
</tr>
<tr>
<td>OHD</td>
<td>Off-Hour Deliveries</td>
</tr>
<tr>
<td>OSM</td>
<td>Open Street Maps</td>
</tr>
<tr>
<td>PM</td>
<td>Particulate Matter</td>
</tr>
<tr>
<td>PPP</td>
<td>Public-Private Partnership</td>
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<tr>
<td>PSO</td>
<td>Particle Swarm Optimisation</td>
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<tr>
<td>RUC</td>
<td>Road User Charging</td>
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<tr>
<td>SC</td>
<td>Social Costs</td>
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<tr>
<td>SCBA</td>
<td>Social Cost Benefit Analysis</td>
</tr>
<tr>
<td>SO</td>
<td>System Optimal</td>
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<tr>
<td>SO2</td>
<td>Sulphur Dioxide</td>
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<tr>
<td>TS</td>
<td>Tabu Search</td>
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<tr>
<td>TDM</td>
<td>Traffic Demand Model</td>
</tr>
<tr>
<td>TR</td>
<td>Toll Revenue</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
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<td>--------------</td>
<td>-------------</td>
</tr>
<tr>
<td>UE</td>
<td>User Equilibrium</td>
</tr>
<tr>
<td>UL</td>
<td>Upper Level</td>
</tr>
<tr>
<td>V/C</td>
<td>Volume Capacity ratio</td>
</tr>
<tr>
<td>VEGA</td>
<td>Vector Evaluated Genetic Algorithm</td>
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<tr>
<td>VKT</td>
<td>Vehicle Kilometres Travelled</td>
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<tr>
<td>VOC</td>
<td>Vehicle Operating Cost</td>
</tr>
<tr>
<td>VOT</td>
<td>Value of Operating Time</td>
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<tr>
<td>WIM</td>
<td>Weigh In Motion</td>
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Chapter 1

Introduction

1.1 Background

Road users are charged differently in various countries to recover infrastructure capital costs, operation and maintenance costs. Fuel tax is the most historical and popular method of charging users, revenue and other forms of license and toll charges played a vital role in reforming road user charge (RUC) in the past. The word “toll” has a broader meaning and in simple terms, it’s a financial tool to charge users or a tool to change user behavior as an implication of a monetary charge. The objective and process deciding such a charge could vary from simple footings such as a charge to recover infrastructure costs or direct user costs (for bridges, tunnels, road sections, etc.) to complex terms where the toll is being used as a traffic demand management tool. For an example, tolls are charged from road users in order to control traffic congestion or to raise finance to recover capital, operational and maintenance cost of roads or as a tool to control emissions or as any other traffic management measure. Therefore, the toll has multiple faces beyond just a financial tool and understanding how each formation effects, not limited to direct road users, but also to all stakeholders is essential to shape future transportation to achieve a more sustainable system.

Public-Private Partnerships (PPP) or Build-Operate-Transfer (BOT) schemes have become common sources of financing infrastructure projects in many countries and tolls
are collected to recover the cost plus a nominal profit for the risk of investment. Private investors are attracted to such investments due to their low risk and high return nature. On the contrary, the public has accepted private investments due to its transparency and rapid nature of construction compared with government authorities. However, in the operational stage, the public is more concerned about factors such as air quality, safety, and noise whereas investors are most concerned about the return on investment, which are in conflict. Nevertheless, toll levels appear to be set for maximizing profits ignoring many public concerns and other related issues at present.

Regardless of the intended objective of charging vehicles on road, many studies in the past have looked at how various road pricing policies would change the behavior of car traffic. But limited studies have been carried out identifying its impacts towards freight user behavior. Demand for freight movement is increasing day to day as populations’ increase, especially in urban cities, which makes freight transportation significant. However, there were only a handful of studies carried out in the past to study the behavior of freight vehicles, especially to understand their response to toll charges.

Unlike in the past, policy decisions neither should be taken nor implemented purely by looking at two main parties, which are owners and users. Stakeholder demands have grown tremendously over the last few decades in all over the world and therefore it is important to identify key stakeholders and their primary concerns with respect to policy issues, such as tolls.

There are five main stakeholders involved in freight transportation, namely, shippers, carriers, receivers, residents and administrators according to City Logistics studies. Different stakeholders have various objectives which may contradict one another. For example, cost optimization is the main objective of almost all stakeholders but not for residents. In the modern competitive business, the cumulative cost has become the governing factor for all decisions. Thus, each and every player in this cost chain tries to minimize their individual cost, having the idea to maximize profits by virtue of optimizing their intended activities. Table 1.1 depicts the stakeholder’s concerns towards toll charges for heavy vehicles.
**Table 0.1: Stakeholders, their goals and problems**

<table>
<thead>
<tr>
<th>Stakeholder</th>
<th>Goals/ Objectives</th>
<th>Problems</th>
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</table>
| **Government/ Administers** | • Efficient and sustainable freight transportation  
• Revenue for infrastructure operations and maintenance  
• Revenue to build new ones or making a profit  
• Safety and liveable cities  
• Energy saving  
• Economic development | • How to price users correctly? What is the Optimum toll for vehicles?  
• How to minimize delays, congestion, crashes, pollution?  
• What are the energy efficient modes of transport and how to promote them?  
• How to manage user demands effectively?  
• How to manage social and political reaction to tolls? |
| **Private Investors**      | • Revenue for infrastructure  
• Minimization of risks involved  
• Improve safety | • Insufficient revenue either due to less demand (number of vehicles as estimated) or restriction on toll prices or incorrect road pricing (toll) |
| **Carriers**               | • Cost minimization, efficient transportation, safety | • High toll charges, availability of infrastructure (supply), congestion and travel delays, receiver demands, unfair taxation |
| **Shippers**               | • Cost minimization, efficient transportation with reliable carriers, safety | • Carrier charges, carrier’s availability with time due to toll, loading concerns |
| **Receivers**              | • On time deliveries, cost minimization, fewer stock-outs, reliable carriers and shippers | • Carrier charges, reliability, quality of transport, delivery times, delivery frequency, stock management |
| **Residents**              | • Quality air, less noise, road safety, aesthetic | • Noise and emissions in the neighborhood due to the use of local roads by HV (toll avoidance) |
From the stakeholder’s goals presented above it’s very clear that financial variables are not the only factor in concern but also social and environmental. Thus, City Logistics concept can be used to handle this problem.

Traditional decision-making process only considers cost as the governing factor, but City Logistics considers social and environmental conditions beyond the cost which recognized under triple bottom line. This concept looks at the overall optimization of freight movement, especially in urban areas. This has been defined as, “the process for totally optimizing the logistics and transport activities by private companies with support of advanced information systems in urban areas considering the traffic environment, traffic congestion, traffic safety and the energy savings within the framework of a market economy” (Taniguchi, 2014; Taniguchi and Thompson, 2002). City logistics is therefore for more sustainable and liveable cities. This can contribute to developing a more efficient and environmentally friendly urban freight transport systems in the future.

When toll charges are implemented authorities expect a change in travel behavior of road users by means of travel time (starting time) and frequency, the decision about the trip (make it or not), mode of travel, or in the long run change in land use pattern. Traffic demand management strategies usually focus on cars and light vehicles, but not much attention is paid to freight vehicles, may be due to the fact that the number of HV is comparatively less on roads.

Freight distribution is more difficult to understand as well as hard to predict due to its nature of the business, such as goods they deliver (perishable vs non-perishable, toxic items, items require special containers, regular items, etc.) and their role is sandwiched
between suppliers and receivers or end customers. As a result, the flexibility they enjoy with respect to decisions that they make regarding deliveries is also limited and this has been further enacted by market competition. Based on the past studies it can be concluded that for-hire carriers’ behavior is somewhat different from private carriers under certain circumstances such as response to road pricing and delivery times (Holguín-Veras et al., 2006).

In deciding toll levels, planners use the simple economic principle that pricing would bring down the traffic demand during peak hours, which is true for rational users due to increased cost, and some may shift to off-hours. This was found to be not true with freight vehicles. Researchers have found that the expected time shift is not taking place with respect to freight vehicles (Holguín-Veras, 2008) due to two reasons. The primary reason is that carriers are not the sole decision maker about delivery times, but the receivers (Holguín-Veras, 2008; Holguín-Veras et al., 2005). Literature has clearly shown that carriers have very less power to decide on time windows and thus the expectation of charging higher tolls to shift HV traffic to the off-peak condition is not achievable (Holguín-Veras, 2011). As a result, deliveries have to be made up on time, as requested by receivers. However, carriers tend to change the route from the toll road to other alternative highways (with no such charges) in order to minimize their individual costs of deliveries (Quak and van Duin, 2010), which is rational, but generating more externalities which detriment public welfare (Swan and Belzer, 2010).

Freight vehicles are known to produce more externalities compared to cars, especially in city limits, where average speeds are low and mostly congested. As a result, freight vehicles in urban conditions produce more externalities such as crashes, noise, emissions, and it was found that conditions were worst due to toll avoiding nature of freight movement. This is elaborated more in Chapter 5 considering both ‘CityLink’ and ‘EastLink’ roads in Melbourne, Australia.

On the other hand, unlike car users, freight vehicles have usually are left with no choice (practical possible) in changing the mode of transport. The only available network is rail, but in most of the countries rail network is either not widespread enough to cover all areas or has no significant demands (scattered demand) to set up one. In addition, it’s
not practically possible to use the rail network for the last kilometer deliveries. As a result, no choice left for freight transportation other than remains on the road network. McKinnon (2006) has confirmed this with reviewing European truck tolling schemes where he found no significant changes in the modal split, despite the higher cost of transport by road haulage. In the long term, carriers may try to change the geographic area of warehouses and distribution centers avoiding toll roads and congested road networks, but the options are very limited.

1.2 Problem definition

The primary objective of freight carriers is to maximize profit and operation cost minimization is one of the major approaches to achieve it. As a result, freight vehicle routes are generally determined by considering the individual cost of operation. At the same time, road tolls are set by service providers, mostly in collaboration with authorities to recover investment cost plus a profit at or above the market rate. Since toll charges increase carriers cost of operation, they tend to avoid such roads and look for alternative roads, mostly arterial or local roads since the change in time of delivery has been found to be not an option based on past studies (even though no tolls or reduced charges at nights). It is important to note that freight vehicles produce more externalities compared to light vehicles and these vary profoundly by road type and speed. Therefore, the toll can lead to producing more costs to society in terms of emissions, noise, air quality (environmental factors), road safety, crashes and congestion (social issues).

Research Question:

*Can toll structures be designed to minimize the total costs of freight in urban areas?*

In other words, it is possible that some cost reductions (e.g. economic costs) may only be achieved at the expense of other costs (e.g. environmental costs) – this is where do these trade-offs come from.
1.3 Thesis goals and objectives

The overarching aim of this research is the development of a Decision Support Tool for Policy Makers (Government) for determining optimal toll charges for freight vehicles while minimizing economic, social and environmental costs.

The objectives of the research are:

- To methodically review the past and present road user charging systems for urban freight vehicles and propose a promising scheme

- To develop a quantitative model to estimate direct the costs and externalities (economic, environmental and social) for various types of freight vehicles

- To understand the decision-making behavior of freight users in Melbourne, Australia

- To understand the objectives of multi-stakeholders and their priorities in Melbourne

- To develop a model for determining optimal toll schemes for multiple classes of vehicles considering both direct costs and externalities

- To develop a framework to identify the trade-offs between various objectives (e.g. emission reduction, return on investment and social costs) of designed toll charging schemes considering given constraints (e.g. maximise toll charges for each vehicle type and minimum return on investment)

- To test the algorithms developed using a case study based on a hypothetical small network

- To demonstrate the application of the developed toll optimization method to a realistic problem using a real-world large network
• To analyze the response of multiple stakeholders to different solutions produced by the toll optimization model

• To integrate all tools and models developed above to support City Logistics concepts

• To develop guidelines for toll-related policy decision-making based on an overall study

1.4 Contributions of the thesis

This research focuses on the development of a model to optimize toll charges for multi-class vehicles considering multiple objectives in relation to different stakeholders’ preference in City Logistics, which has not been done before. As part of this research, a bi-level model is developed to optimize the multi-class toll charges under multi-objective optimization framework. This model provides the information necessary for policymakers to make more sustainable decisions on freight movements in urban areas. In addition, Multi-Actor Multi-Criteria Analysis (MAMCA) provides guidance to policy decision makers to identify what stakeholder objectives are and how such objectives can be prioritized under prevailing circumstances.

1.5 Thesis organization

Chapter 1 provides the general background to urban freight transportation, research problem, goals, and objectives, the contribution of the thesis and an outline of the thesis.

Chapter 2 provides a review on past and present road user charging systems and its drawbacks, and the necessity for a new model looking at multiple stakeholders and their objectives. In simple words, this chapter presents
a literature review to spot the gaps in research and highlights the necessity for a comprehensive model.

Chapter 3 provides the general methodology developed in this research, which is the bi-level optimisation. In addition, the other supporting methodologies used in this study are also presented here.

Chapter 4 provides the approach taken towards developing the direct and indirect costs (externalities) estimation of freight vehicles in the urban context and the final numerical models used in this research.

Chapter 5 elaborates on the current toll charging schemes for two toll roads in Melbourne. This provides additional analysis to strengthen the research problem.

Chapter 6 presents the survey carried out to understand the freight behavior in the urban context of Melbourne and provides the basic information required for MAMCA analysis. In addition, this Chapter provides the ingredients to find out how freight vehicles would respond to toll charges based on Discrete Choice Data collected from the survey.

Chapter 7 evaluates the optimum toll charges for freight vehicles considering multi-stakeholder objectives in urban conditions. This is the main application of the model developed and applied to a small hypothetical network to demonstrate the model (case study 1). Then, the model is validated using a real-world network around EastLink.

Chapter 8 applies a single-objective optimization to the model to find determine multi-class tolls to reduce total emissions on the road network. Since emissions and air pollution from road transport are one of the major problems faced by transport authorities the model has been used to minimise the emissions using multi-class tolls. This application of the model is also illustrated using both hypothetical and real-world networks.
Chapter 9 analyses the toll optimisation problem with multi-stakeholder objectives from a different perspective. This Chapter is focused on elaborating whether subsidies are an effective way to manage this toll problem. The Pareto-optimal solutions developed considering key stakeholder objectives are used to illustrate the trade-offs. The real-world network around EastLink was used to generate results. This analysis provides greater awareness for the decision maker regarding various toll schemes, its trade-offs and where subsidies can be effectively used.

Chapter 10 provides a comprehensive analysis of the stakeholder acceptance of various toll optimization alternatives produced in previous chapters using MAMCA. Since acceptance of any toll policy is critical as discussed in Chapter 2, all multi-stakeholder objectives (found through the survey) were used to evaluate the acceptance of different alternatives.

Chapter 11 provides the overall conclusion of the research and its major findings. Recommendations for future research are also presented.
Chapter 2

Literature Review

In this Chapter a literature review on the problem discussed in this thesis and related areas is provided.

- Section 2.1 reviews the conventional road user charging schemes and how such systems have failed to achieve its intended objective
- Section 2.2 reviews the present road user charging systems practised in some countries around the world
- Sections 2.3 and 2.4 review the City Logistics concept, its applicability in this study and identifies the key stakeholders
- Section 2.5 evaluates road user charging schemes considering multi-stakeholder objectives
- Section 2.6 reviews how tolls have been used as a capital recovery tool
- Section 2.7 reviews the issues encountered in the past when implementing toll related policies
- Section 2.8 highlights the need for a new model and section 2.9 outlines the proposed model
- Section 2.10 provides a summary of the chapter
2.1 Traditional road user charging schemes and its failure

Fuel taxes, permit and registration fees have traditionally been collected to recover infrastructure use costs (Conway & Walton, 2009; Fowkes, Nash, & Tweddle, 1992; Gomez & Vassallo, 2013; Lignier, 2011; McKinnon, 2006b; Newbery & Santos, 1999; Parry, 2008; Winston, 1991) and tolls were charged for various purposes. Fuel taxation started in the 1920s and remains in operation for some countries (including Australia) to recover road usage costs. This tax was initially introduced as a method to recover user costs since it’s very easy to collect and theoretically fuel is a good supplementary product to measure vehicle usage. Thus, fuel consumption was a relatively equitable measure to distribute system costs (Conway & Walton, 2009; Forkenbrock & Kuhl, 2002).

In other words, the more distance you travel or more weight you carry, the amount of fuel burnt is proportional and as a result, the fuel tax is a good indirect way of charging for road usage. These assumptions are now questionable due to the development of more fuel-efficient vehicles, larger truck combinations, progressive penetration of alternative fuels, and thus fuel tax has become an unreliable mechanism to charge for road usage (Broaddus & Gertz, 2008; Forkenbrock & Kuhl, 2002; Gomez & Vassallo, 2013; Levinson, 2010). On the other hand, kilometres driven per litre has gone up (more efficient engines) over time but cost of maintenance never decreased (rather it has gone up) and as a result revenue collected through fuel tax has become insufficient to cover road costs (Downs, 2005; Gomez & Vassallo, 2013; Parry, Walls, & Harrington, 2007; Poole, 2007). Furthermore, when fuel prices drop, the amount of tax collected may decrease if the tax is a fixed percentage of the selling price, e.g. in Australia where tax is a fixed percentage (25%) of the cost (PwC, 2013). Thus, revenue cannot be estimated and a major deficit occurs over time (NTC Australia, 2016a). During recession times a reduction in Vehicle Miles Travelled (VMT) leads to less fuel consumption, generating less tax revenue than expected. As a result of the aforementioned reasons fuel tax is not sufficient enough to support capital and maintenance costs and is found to be an
outdated method as a tool to charge users. This situation is also common in the US and many other countries but they have reformed to use non-fuel based sources of financing that cater to evolving customer demands (Gomez and Vassallo, 2013; HVCi, 2013a; Oh and Sinha, 2010).

The following reasons were highlighted by Forkenbrock (2005) as to why fuel based tax is outdated and inefficient in his study. Heavy vehicles damage the roads more severely but do not pay in right proportion to this damage and sometimes the jurisdiction of fuel purchase and the site of actual travel is not the same. For example, international hauliers in Europe and interstate hauliers in the US always pump fuel from cheap points and travel via countries or states. The motor fuel tax does not give vehicle operators an indication or information regarding the total cost of a particular trip, such as one in congested traffic conditions, may impose on society. It is not possible for government agencies to provide incentives with fuel taxes to vehicle operators to change the nature of their road use, including loading patterns, travelling on high standard roads where damage from HVx could be minimized or shifting to off-peak hours.

Other than the fuel tax, registration charges are another popular charge imposed by authorities around the world mostly without any rigorous rationality. The mere elements considered in determining such charge is a fixed element of infrastructure cost, administration cost and emission level in some countries. As a result, placing greater emphasis on vehicle registration fees is not a good strategy since these fees have a very weak relationship to the amount of road usage by individuals in today’s context and thus the charges are inexplicit (Forkenbrock & Kuhl, 2002).

2.2 Present road user charging schemes

2.2.1 Overview of RUC schemes

Road pricing policies have evolved in numerous ways over time. Cordon pricing, zonal pricing, time or distance-based pricing combined with a variable charge for vehicles based on type, passenger capacity, number of axels, weight, fuel type, and emission are common charging systems nowadays. However, dynamic pricing is crucial to manage
traffic and to achieve intended objectives which are not an easy task since user behavior is not as rational as we always think. Flat tolls are suitable for maximizing revenue whereas time-of-day or responsive tolls are preferable to control congestion (de Palma and Lindsey, 2011). Many road pricing schemes in the past used flat rates due to technological or administrative difficulties in changing a toll (de Palma and Lindsey, 2011).

The introduction of Electronic Road Pricing (ERP) systems has enabled a more efficient and effective way of charging users differently. Computer simulations, mathematical models are used to predict both static and dynamic traffic conditions in the real world and thus charges are determined. Such variable charges are easily implemented through the Electronic Toll Collection (ETC) mechanism, which is a well-accepted method by both authorities as well public due to its inherited advantages for both parties. The electronic system is capable of collecting toll charges without stopping vehicles at exits, which minimizes infrastructure requirements and staff requirements. As a result, there is no disturbance to traffic flow due to this charging exercise and thus no delays or inconvenience for users. Not limited to that, a reduction in stop-go conditions greatly reduces emissions. This technology is very common now and is successfully in operation on many toll roads.

When it comes to traffic demand forecasting and toll roads, models or mathematical predictions are found to be either optimistic or contains large errors (Bain 2009). Therefore, this study has set its boundaries with various toll collection strategies where outcomes are not evaluated in detail. The rest of the sub-section of this chapter reviews the major road user charging systems implemented in other countries of the world to understand the model objectives, charging mechanism, and technology used.

2.2.2 Review of existing RUC schemes

2.2.2.1 Road user charging schemes in Europe

In the past, like any other region in the world, Europe is also charged fuel taxes and some fixed taxes to recover expenditure on its highway system (Fowkes, Nash, & Tweddle, 1992). The aim of the introduction of Eurovignette in EU was to recover construction,
maintenance, repair and environmental costs on their road network. More importantly, ensuring unbiased competition and stopping discrimination among hauliers in the member states. However, this was a time-based charging system that is jointly operated by Belgium, Denmark, Luxemburg, the Netherlands and Sweden (European Commission, 2010). The main problem found with the Eurovignette system was the charges do not consider the distance travels by a vehicle, but the time, and therefore is poorly correlated with infrastructure costs. On the other hand distance-based tolls found to be corresponding much more closely to the cost of infrastructure use (McKinnon, 2006b). Later they changed to the ‘polluter pays’ principle from the ‘user pays’ principle in order to allow for the internalization of the external costs. Many countries came up with their own charging mechanisms considering different aspects. According (Gomez and Vassallo, 2013), in Europe, road generated revenues exceed road expenditures in all the countries studied. This means road charges actually have subsidized other policies. To understand the basic principles a few major policies in Europe are reviewed here.

### 2.2.2.2 German heavy goods vehicles charging system

Heavy good vehicles over 12 tonnes on German motorways have had to pay a distance based charge since 2005, January (Link, 2008; McKinnon, 2006b). This charge was imposed on top of existing taxes and hauliers have continuously argued that the charge was too high.

The German HGV tolling scheme is aimed at goods vehicles over the gross vehicle weight of 12 tonnes to recover the full cost. This includes the all costs of construction, maintenance and operation of motorways and also charging scheme operating cost. The charge level is determined based on vehicle characteristics such as weight, number of axles, and the emission class (Broaddus and Gertz, 2008). The introduction of this charging scheme in Germany in 2005, known as LKW-Maut, resulted in a large number of heavy vehicles avoiding tolls by means of diverting from Western Germany to France where the main highways are not tolled yet (McKinnon, 2006b).

The latest advanced technology is used for the German HGV charging scheme. Satellite positioning and mobile telephone communication technology covers all the required
aspects of such a charging system. A mobile telephone connection was made between the vehicle onboard unit (OBU), which combines a GPS receiver and a digital map and charging center. This acts as the transponder for the charging scheme.

### 2.2.2.3 UK Lorry charging scheme

The British government had planned to introduce a lorry road user charge system (LRUC) in 2008 but abandoned the introduction in 2005 (McKinnon, 2006a, 2006b). The charges would have applied to all trucks over the gross weight of 3.5 tonnes, over the entire road network and offer the varying charges by time of day, road type and zone. The reason for withdrawal was the complexity of the proposed project and the government decided to introduce a simple distance-based user charge system. A device called tachograph was installed to all heavy vehicles over 3.5 tonnes, operating within EU, to measure the distance. This installation was compulsory, and distance traveled during each year was observed at the point of registration and tolls are calculated accordingly. The British government did not charge for the mileage run in other countries by vehicles registered in the UK but engaged in international haulage. A fuel rebate was based on a benchmarked fuel efficiency level in order to omit double taxation. This benchmarked system has certainly penalized vehicles underperforming in terms of efficiency and encouraged vehicles with high fuel efficiencies (McKinnon, 2006a). This toll charging system was purely focused on charging a fair share for using the UK roads by overseas hauliers rather generating additional revenue for transport investments (McKinnon, 2006b).

### 2.2.2.4 Swiss and Austrian heavy vehicles tolling systems

Since 1985 a flat fee for Heavy Goods Vehicles (HGV) was in existence and it was changed to a nationwide distance related fee, named as the LSVA, since the Swiss government predicted a 100% increase in HGV on the Swiss road network as a result of bilateral treaties made with the European Union to extend the maximum weight limit of HV from 28 tons to 34 tons, and to 40 tons later on. After a referendum and a subsequent vote, the LSVA started on January 1st, 2001.
The LSV A applies to all domestic and foreign heavy vehicles transporting either goods or passengers with a maximum laden vehicles weight in excess of 3.5 tons. For domestic vehicles installation of an On-Board-Unit (OBU) was mandatory. Foreign vehicles are predominantly using a ticket fetched at self-service machines. The distances traveled by each HGV, on all public roads (not only motorways) in the country are measured using the tachograph. A tachograph is switched on and off when crossing the border. Charges are calculated based on the distance traveled, maximum permissible vehicle weight and the emission class of the vehicle (Dodoo and Thorpe, 2005). According to McKinnon, (2006b), the objective of Swiss truck tolling is to raise finance to support infrastructure development and majority of the funding raised through the Swiss toll was utilised to construct rail tunnels.

Trucks and buses on Austrian roadways were subjected to time-based toll system until 2004, where distance-based pricing was introduced (Gammelgaard et al., 2006). In Austria, there’s an OBU called ‘Go Box’ and all trucks over 3.5 tonnes of gross weight are required to fix an OBU. Light vehicles still have to pay the time-related user fee based on Vignette. Gross weight and axle configurations (3 classes) are considered when determining road user charge per kilometer traveled, but not emission parameters unlike in Switzerland. Only motorways and express roads are subjected to a toll, as a result, diversion of traffic to local and regional parallel roads were inevitable. However, the proportions are found to be insignificant (less than 2% of the total traffic on motorways).

2.2.2.5 Heavy vehicle charging in the US

In the United States, highway users pay for their roadway use through indirect user fees that are levied at the federal, state, and local level. Federally, the primary sources of truck user fee revenues are fuel taxes. Other federal truck user fees include sales taxes on trucks, tractors, trailers, and tires, and an annual fixed-rate heavy vehicle use tax (HVUT) (Gomez and Vassallo, 2013). These tax rates vary depending on gross vehicle weight (GVW). Other than that, weight-distance tax (WDT), overweight and over-dimension permit fees try to recover some components of the road damage in some states.
The revenue generated primarily through fuel taxes was found to be insufficient to maintain the federal highway system (public sector subsidizes the road system) and many suggestions were proposed in the past as measures to increase revenue. Increasing fuel taxes, at least to keep pace with inflation, spreading the use of toll highways, imposing new taxes and fees, and encouraging private investments such as PPP’s are among them (Brown, 2007; Gomez & Vassallo, 2013; Poole, 2007).

Vehicle Miles Travelled (VMT) based fee has been identified as the most suitable option in the long run in the US because it could establish a reliable source of funding, reduce traffic congestion, promote more efficient use of vehicles with higher loading capacities, and discourage unladen miles traveled. However, implementing a usage-based pricing scheme such as VMT based faced several challenges. For example, public and political acceptance, technology, administration and financial feasibility (Oh and Sinha, 2010) are few of them which are discussed in detail later. As a result of the fuel taxes still exist in the United States (Gomez and Vassallo, 2013).

At present, there are more than 300 toll roads in the USA (Holguín-Veras, Cetin, & Xia, 2006). Most toll roads define their base toll rate structures according to the vehicle’s number of axles and some HVs are tolled according to their registered GVW. Taken together, the analyses conducted by Holguín-Veras et al. (2006) strongly concluded that toll policies across the United States have penalized large commercial vehicles disproportionately. In his study, the toll charges were compared for various types of vehicles considering the following parameters: vehicle lengths, load equivalency factors, consumption of road space and the damage caused to the pavement.

Congestion has emerged as one of the greatest challenges faced by transport planners and authorities in developed economies. It’s a major social cost to the society and the cost was estimated as high as $78 billion in 2005 in the USA and is growing rapidly as a result of speedy increases in travel delays experienced by users every day. The cost was estimated not only in terms of lost time but productivity, air pollution, and energy wasted are considered. As a solution to these severe levels of congestion the U.S. Department of Transportation has recently started a program to initiate congestion pricing in five metropolitan areas (Albalate and Bel, 2009).
State Highway Cost Allocation Studies (HCASs) have a long history in the United States spanning over 70 years. More than 80 studies have been performed in at least 30 states during that time (Balducci and Stowers, 2008). Federal Highway Cost Allocation Studies (HCAS) were completed in the United States in 1997 (FHWA, 1997) and no major changes have occurred since then. According to (Oh and Sinha, 2010), this self-financing scheme was designed to attain maximum efficiency followed by horizontal equity. This comprehensive usage-based charging system will enable self-finance construction, operation, and maintenance cost of the highway system and calculated user fees based on vehicle class, weight, configuration and distance travel on each facility. However, externalities produced by vehicles are not considered in this user charging scheme such as congestion and emissions and thus authors have stated that future studies need to introduce such cost components into the scheme (FHWA, 1997; Oh and Sinha, 2010). In the year 2000, HCAS was revised to reflect social costs calculated by the Environmental Protection Agency (EPA) in the US. As a result, crash, congestion, air pollution, and noise costs were introduced and user fee based on vehicles type and environment condition (urban/rural) was re-calculated (FHWA, 2000). However, these HCAS were not fully implemented in the United States mainly due to a political setting that focuses on painless revenue generation from established sources rather than instigating equity among highway user classes (Balducci and Stowers, 2008).

2.2.2.6 Heavy vehicle charging schemes in Australia

Heavy vehicles (any vehicle or trailer with a mass over 4.5 tonnes) in Australia are subjected to two pricing charges. Namely; a road user charge (RUC) and an annual registration fee. The RUC is a levy on each litre of diesel a HV consumes and presently it’s about 38.14 cents per litre. The National Transport Commissions (NTC) provides recommendations for setting these heavy vehicle charges which are based on a charging framework known as pay-as-you-go (PAYGO). This was introduced in Australia in 1992 (NTC Australia, 2016b; PwC, 2013).

The PAYGO system tries to recover the road usage costs from each heavy vehicle type and to recover a share of common road costs, such as street lighting, rest bays, and signage. The PAYGO scheme follows a simple mechanism to calculate heavy vehicle
charges using the latest heavy vehicle and trailer population data available at NTC. They have considered seven-year averages for both road expenditure and vehicle usage data assuming that charges do not change significantly in response to short-term changes in expenditure or vehicle use (NTC Australia, 2016b; NTC Australia, 2016a).

In Australia, revenue recovered through heavy vehicle charges helps the government to provide better and safer roads. According to NTC, around 40 percent of heavy vehicle costs are recovered as state and territory registration fees, with the balance paid through a fuel-based road user charge which is collected by the Commonwealth Government (NTC Australia, 2016b).

In Australia approximately three-fourths of the HV fleet is owned by ancillaries and rest is by for-hire. It is obvious that for-hire use more road kilometers than ancillaries and registration cost is determined based on a cost-recovery scheme which considers historic expenditure on road services. Therefore, the registration fee determined for vehicle type irrespective of its ownership or real usage leads to very high inequity. In addition, there are substantial variations in registration costs between states in Australia for no valid reason. Therefore, cross-subsidization is very high in Australia.

As mentioned before, in Australia it has become common place for PPPs and there has a growing number of toll roads in main cities and it is claimed that it has the largest (in terms of lane kilometers) urban tolled road network in the world (Li & Hensher, 2010). In general, toll charges in Australia are based on the distance of travel, vehicle type (very broad classification) and time of day. However, toll charges vary over facilities and over sections within the same facility as highlighted by Perera et al., (2016) in their study. Australia firstly introduced an ETC system in the CityLink project for toll collection (Lay and Daley, 2002). Despite the availability of latest technology in CityLink, the appropriateness of toll charges (representing true user charges) stipulated in CityLink road is deplorable. As a result, a noteworthy social dialog has begun among truck community and stakeholders recently in Australia (Carey and Willingham, 2017).
2.3 City Logistics

City logistics is defined as, ‘the process for totally optimizing the logistics and transport activities by private companies with support of advanced information systems in urban areas considering the traffic environment, the traffic congestion, the traffic safety and the energy savings within the framework of a market economy’ (Taniguchi and Thompson, 2014).

‘City logistics is based on system approach which promotes innovative schemes that reduce the total cost, including economic, social, and environmental cost of goods movement within cities’ (Taniguchi and Thompson, 2002). The systems approach (Taniguchi et al., 2001) divides a larger problem into pieces and arrives at a solution systematically. Therefore, this approach is used to solve many problems in the freight industry and to provide more sustainable solutions. Thus, a systems approach is used in this thesis to review road user charging systematically and to propose valid solutions.

Furthermore, City Logistics has attracted a large amount of research interest during the last decade and this has produced many promising results for improving urban freight transportation. In the recent past, studies have been undertaken exploring more avenues for city logistics such as an integrated platform for innovative city logistics with UCC and transhipment points by (Taniguchi et al., 2018), crowd based city logistics (Sampaio et al., 2019), implementation of city logistics theories (Russo and Comi, 2018), public-transport based city logistics (Gatta et al., 2018) and multi-modal last mile delivery (Perboli et al., 2017).

Urban freight transport related studies also fall into the city logistics domain even though it’s not explicitly mentioned. Predicting travel patterns of freight vehicles in an urban context (Oka et al., 2018), electric vehicles in urban freight transport (Mirhedayatian and Yan, 2018), stakeholder perspectives and engagement (Duin et al., 2018; Marcucci et al., 2018), urban freight policy making (Akgün et al., 2019; Janjevic et al., 2019), impacts of off-hour deliveries (Holguín-Veras et al., 2018c), urban freight management (Dahlberg et al., 2018; Holguín-Veras et al., 2018a&b), emission reduction
from urban freight transportation (Goetz and Alexander, 2019) and delivery times (Eren Akyol and De Koster, 2018) are some recent studies in urban freight domain.

## 2.4 Stakeholders

Problem definition is the first main step in the systems approach. Since the problem has multi-tiers it is important to identify the multi-stakeholders, their objectives, and their problems.

<table>
<thead>
<tr>
<th>Stakeholders</th>
<th>Problems</th>
<th>Goals/ Objectives</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Government/Administers</strong></td>
<td>Insufficient revenue, users demand better solutions, users hesitant to pay taxes, delays, congestion, crashes, pollution, energy inefficient modes of transport</td>
<td>Revenue for infrastructure maintenance and to build new ones, safety and liveable cities, efficient and sustainable mode of transport, energy saving, economic development</td>
</tr>
<tr>
<td><strong>Carriers</strong></td>
<td>Operational cost, RUC, infrastructure, travel time, receiver demands</td>
<td>Cost minimisation, efficient transportation, safety</td>
</tr>
<tr>
<td><strong>Shippers/Receivers</strong></td>
<td>Carrier charges, reliability, quality of transport, delivery times, delivery frequency, stock management</td>
<td>On time deliveries, cost minimisation, less stock outs,</td>
</tr>
<tr>
<td><strong>Residents</strong></td>
<td>Crashes, congestion, noise, emissions, land use, modes of transport, TOD travel,</td>
<td>Quality air, less noise, safety, aesthetic appearance, efficient transportation, liveable cities</td>
</tr>
<tr>
<td><strong>Private Investors (road infrastructure)</strong></td>
<td>Demand &amp; toll charge</td>
<td>Return on investment &amp; safety</td>
</tr>
</tbody>
</table>
2.5 Evaluation of RUC schemes considering multiple stakeholder objectives

A critical evaluation of the key schemes reviewed above was done by identifying the strengths and weaknesses of each scheme with respect to multi-objectives listed under stakeholders (refer to Table 2.2).

**Table 0.2: Strengths and weaknesses of emerging user charging approaches**

<table>
<thead>
<tr>
<th>Scheme</th>
<th>Strengths</th>
<th>Weaknesses</th>
</tr>
</thead>
<tbody>
<tr>
<td>German</td>
<td>*Costs fully recovered</td>
<td>*High toll charges</td>
</tr>
<tr>
<td></td>
<td>*Emissions considered-encourage efficiency</td>
<td>*Not on all roads (toll avoidance)</td>
</tr>
<tr>
<td></td>
<td>*Technology used</td>
<td>*LGV are not charged</td>
</tr>
<tr>
<td></td>
<td>*Eliminated cross-subsidization (foreign hauliers)</td>
<td>*Noise issue not considered</td>
</tr>
<tr>
<td></td>
<td>*Most factors that contribute to usage been used to determine the charge</td>
<td>*TDM is not considered</td>
</tr>
<tr>
<td></td>
<td></td>
<td>*Fuel tax</td>
</tr>
<tr>
<td></td>
<td></td>
<td>*HV over 12 tonnes are considered</td>
</tr>
<tr>
<td>UK</td>
<td>*Fuel rebate</td>
<td>*Distance based cost, not perfect</td>
</tr>
<tr>
<td></td>
<td>*Encourage fuel efficiency of vehicles</td>
<td>*Externalities are not considered</td>
</tr>
<tr>
<td></td>
<td>*Partially direct method</td>
<td>*TDM is not considered</td>
</tr>
<tr>
<td></td>
<td>*All roads are tolled</td>
<td></td>
</tr>
<tr>
<td></td>
<td>*No additional charges (fair)</td>
<td></td>
</tr>
<tr>
<td>Switzerland</td>
<td>*All roads are tolled</td>
<td>*TDM is not considered</td>
</tr>
<tr>
<td></td>
<td>*Partially direct method</td>
<td>*Fuel tax</td>
</tr>
<tr>
<td>Austria</td>
<td>*Partially direct method</td>
<td>*Emissions not considered</td>
</tr>
<tr>
<td></td>
<td></td>
<td>*TDM is not considered</td>
</tr>
<tr>
<td></td>
<td></td>
<td>*Fuel tax</td>
</tr>
<tr>
<td></td>
<td></td>
<td>*Not on all roads (toll avoidance)</td>
</tr>
</tbody>
</table>
| USA       | * Partially direct method  
| * Congestion pricing in some areas | * Fuel tax  
| * Not on all roads (toll avoidance) | * Cross-subsidisation still exist  
| * Externalities are not considered |
| Australia | * Simple and conventional method | * Fuel tax  
| * Not linked with direct usage (cross-sub) | * Externalities are not considered  
| * TDM is not considered | * Not on all roads (toll avoidance)  
| * High and non-transparent toll charges |

### 2.6 Toll as a capital recovery tool

Tolling is a financial charge imposed on road users either to raise finance (recover cost of infrastructure) or to change their travel behavior. Toll charges may be used to recover capital investment (spent on infrastructure development) or as a traffic management tool if variable pricing is adopted based on demand. Using toll charges to recover capital investment has a long history starting back in the 15th century where tolls were charged to recover the construction costs of bridges and tunnels. Beyond the usual framework, tolls are charged in some countries to control emission in cities.

It was Pigou’s idea in the first place that charging tolls would lead to more efficient use of road space (Holguín-Veras and Cetin, 2009). Today toll charges are a widely discussed topic due to a number of reasons. Firstly, and most commonly, tolls are being charged in order to recover the investment and related costs or to finance a new facility (e.g. in Tokyo, Japan). This concept has become popular with Public-Private Partnerships (PPPs) (Chen and Subprasom, 2007). The use of PPPs for new infrastructure development is rising, particularly in Europe, developing countries, Latin America and Australia (Li &
The popularity of PPPs is growing in the world due to a number of reasons. Rapid growth in public demand over more infrastructure and constraints on public budgets have hard-pressed the authorities to look for alternative financing options, creating the demand for such investments, while clear terms of returns stipulated in PPP contracts have attracted the private sector (Chung et al., 2010; Leccis, 2015) balancing the supply side. The latest trend in toll roads is to charge high tolls for heavy vehicles (Broaddus and Gertz, 2008; Odeck and Bråthen, 2002).

Secondly, charges are being applied to infrastructure facilities to control their usage due to congestion, maximizing social welfare and lately to control emissions in central city areas (Li et al., 2008). Some toll charging programs are very successful in the world, namely, congestion charging in Singapore, London, Stockholm, Valletta, and emissions-based charging in Milan.

In 1975 Singapore introduced an area based pricing scheme (Goh, 2002) as a congestion management tool for the first time in the world (Hau, 1990). Charges were imposed to control a number of vehicles entering city limits and charges vary by time of a day. Many cities introduced congestion pricing to manage traffic at city limits since then. Apart from Singapore, London (UK), some metropolitan areas in the USA, and Stockholm (Sweden) are major success stories in congestion charging in the world. Transport researches have carried out large number of research to find out optimum toll charge for congestion control with different parameters (Albert & Mahalel, 2006; de Palma, Kilani, & Lindsey, 2005; Liu & McDonald, 1998; Wie, 2007; Wie & Tobin, 1998; Yang & Hai-Jun, 1997; Yang & Meng, 1998; Zhang & Yang, 2004). In the year 2008, Milan (Italy) introduced a slightly different urban pricing scheme which was to curb the pollution in the city of Milan (Rotaris et al., 2010). Charges are based on the Euro emission standard of the vehicle entering the city and have achieved its objectives successfully.

Interest in toll road construction has been renewed recently due the advances in tolling technologies and making tolls more efficient and convenient (Fisher and Babbar). Private toll roads are widely constructed in developing countries such as India, Thailand, Indonesia, Malaysia and Philippines.
Usually, public acceptability of toll charges is very low, but this attitude could be positively changed if road users achieved improved roads based on the money collected. When setting up toll prices, States may have a genuine interest on maximizing throughput as well as maximizing revenue, but these two are inherently conflicting each other and impossible to satisfy simultaneously (Gross and Garvin, 2011). From the public point of view toll affordability, congestion management, income maximization/subsidy minimization aspects are carefully considered before accepting such a policy (Gross and Garvin, 2011). More aspects of acceptability are discussed later in this chapter.

2.7 Issues encountered implementing policies

2.7.1 Review of political and social acceptance of tolls

It is a well-established fact that an introduction of a new tax or toll is not usually welcomed with open arms by the public. As a result, any transportation solution that involves such a levy has a political implication and complicated to choose (Poole, 1992; Winslott-Hiselius, Brundell-Freij, Vagland, & Byström, 2009). Usually political and public acceptance is linked together where public opinion is of most concern by politicians. As a result, it could be stated that road pricing schemes are politically accepted only if it gets sufficient public support. On the other hand, it has been found that strong political decisions are a positive measure of higher public acceptance (Winslott-Hiselius et al., 2009).

Road pricing schemes, known as the first-best solution in theory (Jakobsson et al., 2000), could be limited to the drawing board unless political and public acceptance is achieved. Even though economists are certain about its intended benefits (De Borger and Proost, 2012; Lave, 1994), many past proposals have proven that public and political acceptance is a must for successful implementation of such a scheme regardless of how technically well it sounds or extent to what socio-economic benefits it could generate (Anas and Lindsey, 2011; De Borger and Proost, 2012; Goh, 2002; Jakobsson et al., 2000; Kottenhoff and Brundell Freij, 2009; Winslott-Hiselius et al., 2009).
Nevertheless, the most refined and reflective policy design will create some losers and induce opposition. In fact, from the past failures, it can be stated that lack of public acceptance, correlated with political acceptance, has been the most important obstacle to implement road pricing charges. Among many such failures reported in the world, cordon schemes were rejected by public referenda in Edinburg and Manchester (Anas and Lindsey, 2011), combined cordon and zonal scheme for Manhattan stopped by the New York state legislature in 2008 (Anas and Lindsey, 2011) and the congestion metering proposal that was rejected in the city of Cambridge are few of them. According to Ison, (1998), the Cambridge proposal was considered as a concept in the right place at the wrong time reasoning out the public refusal.

As mentioned above, a systematic economic rationale does not always assures political acceptability (Ison and Rye, 2005). Politicians are always keen to apply known or well-established measures such as fuel taxes and registration fees since these measures are more acceptable than those that are less known or unknown ones and generate revenue effortlessly (Link, 2008). Studies from Europe have found that the acceptance of tolls by stakeholders is high when it is applicable to all type of vehicles across all countries in Europe. This indicates that equity is of great concern by stakeholders. In conclusion, policymakers should definitely endorse the perception of fairness into road pricing to gain stakeholders acceptability (Di Ciommo et al., 2013).

Identification of key stakeholders and their expectations are crucial for the successful implementation of road pricing schemes. Different stakeholders seem to have various expectations which may not be in line with the objectives of the road pricing scheme and thus create a negative voice. But there were many proposals that failed in the past with perfect schemes due to poor presentation, unclear objectives or improper timing (Ison, 2000, 1998). As a result, it can be concluded that clear objectives, effective communication, and re-investment of revenue are necessary to win the majority of the stakeholders. As per the prediction of the approach-avoidance theory, public attitudes were mostly adverse just before the introduction of road charges but this dynamic attitude could be changed with test runs (Winslott-Hiselius et al., 2009).
As explained in cognitive dissonance theory (Schade and Baum, 2007; Winslott-Hiselius et al., 2009) people initially tend to refuse the road pricing scheme if effects of the implementation are doubtful, however, more people react positively if the effects of the proposal are known. Therefore, uncertainty among policy makers and politicians about the scheme, usually based on its promised results, may lead to more anxiety when trying to win public acceptance (Viegas, 2001). At the same time, non-availability of a similar system for comparison or may be a success story to rely on could reduce the acceptance of such schemes at the introductory level (Ison, 1998). In summary clearly stated objectives, the process and type of data collection and associated technology, and how the revenue raised from the charge is disbursed and detailed information about implementation costs are critical factors that need to be given careful consideration before announcing a road pricing scheme.

Equity issues make the policy proposal politically weak. Horizontal equity and vertical equity are two dimensions which policymakers work on when distributing revenues generated from road pricing. However, who deserve the benefits is yet to be debated according to Litman, (1996). It could be those who actually paid the toll or those who change their trip patterns in response to tolls providing a better condition for toll users. In the early nineties, Lave (1994) argued that the, “political response will depend on the relative numbers of losers and gainers and the amount of utility lost by those motorists who are priced off”. But this has grown to a far more extent over the years where equity is concerned.

Apart from whether the public accepts this proposal or not, it was found that politicians have concerns about technology requirements, costs of technology and administration sometimes. Furthermore, enforcement issues and uncertainty with data collected (privacy issues) makes them more worried before presenting to the public (Ison, 1998).

**2.7.2 Technology, cost and privacy of data**

Supporting technology for effective collection of RUC in terms of tolls is a must for the successful implementation of any RUC scheme. Starting from manual toll collection systems in early days, where toll booths were maintained with human support to collect tolls or with automatic coin machines (Zarrillo et al., 1997) have transferred to more
technical based systems such as video or CCTV cameras based systems with the aid of license plate recognition software’s and so on. For example, infrared cameras with ANPR technology have been deployed on routes into the Stockholm city center (Hensher and Puckett, 2007). Initially, the tolls levels were kept flat due to charging (technical) and administrative difficulties (de Palma and Lindsey, 2011) but with the advent of new technology such as automatic vehicle identification (AVI) systems make it feasible to invent sophisticated pricing systems in a user-friendly manner (Poole, 1992).

The present era of this technology is Electronic Road Pricing (ETC) which uses gantries and beyond that satellite-based ETC systems (Hensher and Puckett, 2007) are now in place in Germany to charge lorry road users. A mobile telephone or GSM-based technology has been discussed for some time, but the idea was rejected majorly due to privacy issues. The next generation of technology for RUC could be GPS (satellite) based charging mechanism where data pertaining to many parameters such as time of the day, location (geographical location and corresponding road type in use), speed profile, distance traveled, time held up in congestion can be collected promptly. Once data is ready it’s just a matter of time to calculate user charge for each vehicle both in terms of direct and externalities using the available schemes, given suitable schemes are available and imposing them on users.

It is worth mentioning that technology used for road pricing charge has led to a number of problems in the past at the implementation stage and some schemes were even abandoned as a result. Gaining political and public acceptance in the technology used is yet another hurdle in road pricing schemes. When Cambridge tried to introduce congestion metering, the complexity and acceptability of the technology were perceived as a major disadvantage (Ison, 1998). A device was introduced to be fitted on each vehicle and there were many negative concerns regarding such installation. Respondents expressed that a scheme with less-advanced technology would be more acceptable in the first instance (Ison, 1998). Similarly, in Hong Kong, the public was doubtful about electronic road pricing technology, which was new, untested in a real situation and more likely to fail (Borins, 1988). Further, the public was suspicious that the government would use this data to tax drivers callously in the future and thus only a few agreed to have their cars fitted with electronic number plates (Borins, 1988). Also,
some groups in Hong-Kong were opposed to electronic road pricing considering it as being technically unrealistic, ethically suspect, absurdly expensive, and socially divisive (Borins, 1988). Invasion of privacy is also challenged by the public when this nature of advanced technology is used on roads (Borins, 1988; Hau, 1990; Ogden, 2001). Past experience from Taiwan shows that initial acceptance of ETC was lower than expected (Chen et al., 2007). On the other hand, studies from the UK have shown that this is one of the least concerned items by respondents in the UK (Ison, 2000). Therefore, it can be concluded that technology and data privacy is decisive for introducing and promoting road pricing scheme and needs to be handled carefully.

Electronic toll collection (ETC) systems were first implemented in Bergen, Norway in 1986 and in many other places afterward before Singapore implemented it for cordon pricing (Tuan Seik, 2000) for the first time in the world. Holguín-Veras & Wang, (2011) studied the acceptability of technology by freight vehicles, especially acceptance of ETC system. From the study, it was found that freight vehicles do not accept electronic tags compared to private cars due to various reasons. Unawareness was found to be the greatest challenge faced by freight vehicles hindering usage of ITS features. Business attributes and attitudes towards technology were found to be highly correlated with freight carriers willingness to accept technology.

The traditional weight limit enforcement is by static weighing. Weighbridges, wheel and axle scales are used to measure gross vehicle weight and wheel or axle loads (Jacob and Feypell-de La Beaumelle, 2010). Fixed or portable, static weighing systems suffer from a number of limitations. Time taken, staff requirements and practical difficulties to measure each and every truck on a highway are major issues. With the development of technology, high-speed weigh-in-motion (WIM) technology has resolved key issues. A more sophisticated version of WIM sensors is available today in the market which can be fixed to the vehicle and communicate with a central control centre.

Usually, the cost of operation is a major consideration in the implementation of a more equipped, technically advanced system and it was found to be approximately 20% of the revenue collection based on the literature. However, this was found not to be the case with the Swiss system, being 4-6% of the revenue which is comparatively very low. Thus,
it can be considered as the cost is not a constraint anymore for this nature of the application. Moreover, it’s a well-accepted fact that technology is advancing every day and more cost-effective devices are coming into the market.

2.7.3 An unexpected response to road charges by freight vehicles

Planners expected based on the simple economic model assumption that pricing would bring down the traffic demand during peak-hours and some may shift to off-hours. However, researchers have found that the expected reaction is not taking place with respect to freight vehicles where their reaction to road pricing is not by means of shifting to off-hours but by other means (José Holguín-Veras et al., 2006).

In a simple terms, carriers seem to be the decision makers with respect to deliveries they make. Due to high market competition in the carrier industry, especially for-hire carriers, they react to price increases by absorbing it in ways of productivity improvement or changes in facility usage. They try to transfer the price at last resort which is not an easy option as per past studies (Holguín-Veras et al., 2007, Quak and van Duin, 2010). The condition is slightly different for private carriers where transfer pricing or decision making would take place at the first instance at the corporate head office (Holguín-Veras, 2010).

It was found by many researchers that delivery times for freight is decided by receivers or jointly, but not solely by carriers (Holguín-Veras, 2011; José Holguín-Veras et al., 2006). Thus, road pricing does not make a significant influence on receivers to change their decision due to many reasons.

Carriers are willing to shift to night time deliveries due to less congestion, high speeds, being able to do multiple trips, easy to find parking spaces, but receivers are not willing to accept goods at night due to high operational costs for them during off-hours. Operating off hours is much more costly for receivers due to OH’s, wages, overtime chargers, etc. (Holguín-Veras, 2008; Quak and van Duin, 2010). On top of that additional insurance and security costs make the conditions worst. For all receivers it’s not the cost
that hinders OHD. Some receivers are reluctant to accept off-hour deliveries due to the fear of stock out condition. And for some other receivers, the main obstacle to off-peak deliveries might be product availability, as fresh food is typically not delivered during off-peak times (Holguín-Veras et al., 2005).

On the other hand, carriers do multiple deliveries and the toll charge is usually split among 5-6 customers where the price signal is weakened when it reaches a receiver (Quak and van Duin, 2010). Anyhow the price signal (congestion price charged per truck) is too small for the receiver (even if fully transferred to them) to consider as an element for the decision to shift their deliveries due to extra costs (Holguín-Veras, 2010).

Empirical evidence indicates that freight road pricing may not be the most effective way to move truck traffic out of the congestion hours (Holguín-Veras, 2008). Traffic simulations have estimated that general traffic could increase by 2.4-4.7% and that environmental pollutants could be reduced by 5-10% (3-Yannis et al., 2006). Therefore authors suggest that additional incentives need to be given for freight receivers in order to accept off-hour delivers which can compensate receivers extra cost, fully or partially, to achieve benefits (Holguín-Veras, 2008).

In conclusion, it can be mentioned that freight vehicles response and behavior is highly neglected when road pricing schemes have been implemented in the past with more focus being given for private vehicles usage (passenger transportation) where the majority of research exists. Since freight transportation is not a major component when compared to passenger transport and thus the influence that they can create is less. As a result, planners are more concerned with providing alternatives for passenger transport when road pricing schemes are introduced but have neglected freight vehicles assuming that their travel times are much more flexible, which has been found to be not true anymore since the delivery decision does not involve carriers solely. This could vary from country to country and it is evident that proper information about the local context is needed when managing City Logistics. Therefore, in order to shift freight vehicles from peak to off-peak hours, more studies are required to understand their decision-making behavior and costs/benefits involved in the process and what alternative options are available for them in the long run.
2.8 The need for a model

It’s a well-known fact that heavy vehicles do the greatest damage to pavements, not passenger vehicles (Dodoo & Thorpe, 2005; Parry et al., 2007; Sathaye, Horvath, & Madanat, 2010). As many studies have stated (Cebon, 1989; Dodoo and Thorpe, 2005; Fowkes et al., 1992; Salama et al., 2006), pavement damage is a function of many variables such as actual loads, distance travelled, number of axles, axle combination, space between axles, tyre type and configuration, suspension type, load distribution among axles, speed and load capacity of the vehicle and pavement type (flexible or rigid). It was found that the relationship between axle loads and pavement damage is exponential (Chou, 1996; Dodoo and Thorpe, 2005; Fowkes et al., 1992; Ren et al., 2016; Sathaye et al., 2010) which leads to more attention to HV.

Even though pavement damage is the most significant and direct user cost that needs to be recovered, proper calculation and apportionment were lacking in all the schemes discussed above. The German scheme considered some of the parameters in their scheme and some basics are considered in the Swiss and Austrian schemes. Yet, a complete scheme was not introduced to assign the true pavement damage caused by heavy vehicles.

Social and environmental costs (externalities in terms of crashes, congestion, emission, noise, infrastructure cost) that are generated by motor vehicles, especially HVs are becoming more of a concern for societies today. When the feasibility of projects are evaluated these externalities are now incorporated by way of undertaking Social Cost Benefit Analysis (SCBA) beyond the economic BC ratio (Litman, 2009). From a societal perspective, it is desirable for all transportation users to pay their full costs including private and social (Forkenbrock, 1999). Therefore, it is fair to charge the total cost from heavy vehicle users where equity is maximized. Social and environmental costs are not direct costs but are borne by society (Lignier, 2011). Perera et al., (2016); Y. Yang, Perera, Thompson, & Liu, (2016) have studied the social and environmental costs generated by HVs using different types of roads and highlighted its significance. This discussion clearly proves that how sensitive the toll decisions are in terms of total cost and stakeholder objectives.
Only a few schemes have considered emission classes when deciding tolls, namely, German, Swiss and UK schemes. But more parameters need to be incorporated in order to capture the real effects of externalities. Therefore, a more comprehensive model is required to determine toll levels and how to minimize impacts while providing an efficient service.

Furthermore, it was found that toll charges are determined without any acceptable basis and methodology is not transparent to users. Japan has introduced ETC system with the intention of collecting finance (Sumalee, 2004) and as mentioned earlier there’s a trend in the world to charge HVs excessively (Broaddus and Gertz, 2008; Odeck and Bråthen, 2002). The CityLink road in Melbourne is one of the most recent examples of that. Perera et al., (2016) has previously discussed (early 2016) that CityLink toll charges are significantly higher and lead to more externalities being produced due to the toll avoidance nature of HVs. Ignoring this fact, CityLink has increased the toll charges for HGVs a couple of times (increase is about 2-3%) during the year 2016, which makes the conditions awful and recently they have increased toll charges by 125% from 1st of April 2017 to support new infrastructure development (Carey, 2017). This has led to a noteworthy social dialog being initiated among the truck community and other stakeholders recently in Australia (Carey and Willingham, 2017). Another example supporting the same idea, again from Australia, would be the latest toll increase publicized for HVs in Brisbane on the Clem7, Legacy Way, Go Between Bridge toll roads (Atfield, 2017). A comparison was made with car tolls, which was 2.65 times for HVs and will reach 3 with the new hike. All these examples highlight the fact that there seems to be no scientific basis or model available for governments to negotiate with toll companies in PPPs or to determine optimal toll for trucks looking at system optimization, which leads to very an inefficient HV transportation system.

It was found that toll avoidance behavior is a common issue around the world (Albalate and Bel, 2012; Gammelgaard et al., 2006; McKinnon, 2006b; Perera et al., 2016) and excessive toll charges aggravate such avoidance. In Japan, toll avoidance has become a problem where the network share of traffic volume on toll roads has fallen below the average of other countries (Matsuda et al., 2005). In particular, freight carriers try to maximize their profits by minimizing transportation costs, thus tend to avoid toll roads
since cost transfer is not possible due to competition (McKinnon, 2006; Quak and van Duin, 2010). For example, McKinnon, (2006) stated that as a result of European truck tolling schemes, HV’s are likely to re-route where suitable alternative route exists in order to avoid toll charges. In Germany, up to 5%, truck traffic is diverted away from motorways to minor roads to avoid charges and there were complaints from local residents regarding this shift. In Austria, truck traffic increased by 60% on some secondary roads after toll charges were implemented on the main corridors (McKinnon, 2006b). With logistics sprawl, as studied by Aljohani & Thompson (2016), demand for faster routes will grow in the future. As a result, the number of heavy vehicles avoiding toll roads in the future will be higher in the absence of proper toll charges. Toll avoidance leads to severe equity issues and cross-subsidization by road users. This condition is found to be truly unfair for people who are not using the un-priced road network and substantially advantage HVs using the road heavily every day for zero charges (HVCI, 2013b). Therefore, it can be proven that direct road user charges are more appropriate and essential to be applied to all roads before differentiating any freeways or infrastructure that has been developed under private investment schemes. This is well understood in countries like Switzerland, the UK and New Zealand where the entire road network has been tolled (Bereni, 2012; McKinnon, 2006b). Toll avoidance is not limited to an equity issue or cross-subsidization. It also produces more externalities, high maintenance costs on alternative roads and results in less sustainable transportation systems (Gammelgaard et al., 2006; Perera et al., 2016; Yang et al., 2016). So far there has been an only limited number of models developed for investigating the effects of city logistics schemes to evaluate these trade-offs (Taniguchi et al., 2003).

When it comes to externalities produced by freight vehicles, we are not aware of any studies that have integrated all the externalities produced by freight vehicles in optimizing freight transport systems in an urban context with or without considering the effects of toll charges. However, a few isolated aspects have been studied by some authors. Teo et al., (2012) evaluated truck operations in the city to keep pollution levels at minimum comparing cordon based and distance-based pricing schemes. Taniguchi and van der Heijden (2000) presented a model for evaluating city logistics initiatives in terms of carbon dioxide emissions and concluded that cooperative freight transport
systems are most effective in reducing carbon dioxide emissions when freight demand increased.

Therefore, from the literature, it is quite evident that a comprehensive model to charge road users, especially for heavy vehicles is overdue. The following section describes an approach for developing a model.

2.9 The proposed model

Future transport and financial policy objectives require a comprehensive design of pricing schemes to jointly address the efficient and equitable use of road networks, manage congestion, and account for externalities and financing of new infrastructure. New technologies can help imposing variable charges on different classes of users, vehicles, and roads. Demand and capacity utilization can be managed through behavioral responses to pricing and improve network performance (Tsekeris and Voß, 2008). The ideal road pricing scheme should be dynamic (Holguín-Veras et al., 2006) and may consist of a number of sub-models which cumulatively produce a coherent road user charging system for the future. A model should address the objectives of multi-stakeholders.

The intended objectives and benefits of the proposed model are as follows. These objectives try to address multi-stakeholder problems and their objectives highlighted in this chapter and attempts to fill these gap with a new model.

✓ A comprehensive model that directly charges users for what they have consumed (no indirect charges based on supplementary products, transparent, maintains equity)
✓ No cross-subsidization of user costs
✓ No subsidization of transport costs to other forms of revenue
✓ Proper timely maintenance of the road network since the required money is available
✓ The real cost of transportation will be known to users (detailed, transparent calculation). This may help to shape the industry the most efficient way.
This leads to a more sustainable transport system in the future which encourages;

- Fuel efficient, safer fleets with high capacities
- Optimum loading conditions leading to high load factors and efficiency (less unladen trips)
- Optimum routing, less pavement damage, less burden to society
- Long term land use planning and control (Ex: location of warehouses, transshipment, etc.)
- Leads to more efficient logistics systems such as Urban Consolidation Centres and load pooling (vehicle sharing by different logistics providers)
- Mode shift from heavy freight vehicles to other sustainable transport modes such as rail or inland waterways if possible
- Outsourcing transport services is another option where private hauliers usually suffer from less load factors
- New industry practices such as JIT can be supported by re-structuring carrier’s fleets based on different size of vehicles with less toll charges. However, increased frequency of travel, less mass transport leads to increases in costs, but since the real cost of transportation is calculated it can be transferred to receivers and thus decisions will be made by receivers looking at marginal benefits.

Considering the above issues, there needs to be a modeling methodology developed for determining the optimal level of road user charges for freight vehicles in urban areas that consider the objectives of key stakeholders as well as the social, environmental and economic impacts.

The model outlined needs to be capable of charging users directly for what they have really consumed, and this model promotes a more sustainable transportation system. However, the future of freight transportation should look at more proactive manner shaping freight transport to its maximum possible way. In other words, the pricing structure should encourage users to move goods at its lowest possible cost, including externalities.
Charging users based on direct usage (including externalities) is not sufficient enough to create a sustainable transportation system where users behave independently. Thus, it is suggested that a pro-active method where RUC are used as a tool to optimize the total cost of transportation. A system optimized traffic assignment can be achieved if RUC are used as a tool to push users to such an optimum state (which is practically difficult to achieve). This will enable total travel cost to be minimized while minimizing externalities.

Therefore, this will be a multi-objective optimization task considering multiple classes of heavy vehicles as well as economic, social and environmental costs and benefits. Since these multi-objectives are interconnected and sometimes conflicting, it is not easy to find a solution for such conditions. However, bi-level optimization techniques can be used in such circumstances where leaders followed by users and many researchers have used it to solve transportation problems (Labbé & Violin, 2013; Li, Wang, Sun, & Yuan, 2013; Tawfik & Limbourg, 2015; Yamada, Russ, Castro, & Taniguchi, 2009).

The schematic shown below in Figure 2.1 depicts the model development flow chart with key components discussed above.

![Figure 0.1: Model development flow chart](image)
2.10 Chapter summary

Various road user charging mechanisms have been adopted by different countries under various programs aiming at one or multiple objectives. A strong argument in the literature is that fuel taxation and registrations fees are imperfect tools to cover road user charges and more importantly the externalities. However, fuel taxes and registration fees still exist as a direct method to recover road user costs in many countries mostly due to political or public resistance. User demands have grown for more usage-based charging systems and some countries have taken steps to achieve that fully or partially. Charging schemes developed and implemented have considered distance, emissions, and pavement damage, and congestion factors, all or few, by some countries to a certain extent in order to cover direct impacts caused by HVs, but still there are gaps.

More rational methods of calculating road user charges are being hindered by technological, political and social acceptability in the phases of data collection methods, implementation procedures followed by non-availability of models to calculate damage caused to environment and society in the past. Moreover, the complexity of the solution holds the implementation of an ideal system on one hand and political and social acceptability on the other.

This Chapter has reviewed major existing road user charging mechanisms in the world, their key attributes, strengths, and weaknesses. Subsequently, in this Chapter has suggested a more transparent, yet efficient, method for determining road user charges which incorporates the objectives of key stakeholders and the triple bottom line which can be used to improve the sustainability of urban freight transport in the future.
Chapter 3

Methodology

3.1 Research approach

The first two Chapters (Chapter 1 and 2) of this thesis have defined the research problems, goals and objectives, and the framework of the model required. Therefore, the contribution from this Chapter is to develop the methodology to achieve the given research goals and objectives. The flow chart shown in Figure 3.1 demonstrates the main steps followed in this research. Phase two is the core of this research, which is the model development and this Chapter is mainly focused on explaining the model development.
3.2 Phase one

Phase one of this research is to understand the problem, key stakeholders, their objectives and to determine the research methodology to solve the problem stated. The literature review is the main methodology followed under this phase finding out the key stakeholders and their objectives. At the same time, many methods are also elaborated looking at avenues to solve the problem stated. Chapter 1 has given more details about the research problem development and Chapter 2 provides a comprehensive cover in related literature. In addition, Chapters 7 and 8 also provide relevant literature for this research problem.

Since the problem defined in this research is based on a real practical problem that exists in Melbourne, Australia, an additional study has been done to examine the present toll...
charging structures in comparison with the direct and indirect costs for freight vehicles. This study was presented at the ‘Australasian Transport Research Forum 2016’ and the conference paper is included in this thesis as Chapter 5. Based on the present toll charges applied for both CityLink and EastLink (the two main toll roads in Melbourne) analysis was carried out to find out the impact on freight vehicles considering their direct and indirect costs. Findings from this analysis provided a good platform for this research to build on.

3.3 Phase two

3.3.1 Bi-level model development

Many real-world problems involve a hierarchical relationship between two decision levels, often found in engineering, which is a special case of multi-level programming (Vicente and Calamai, 1994). In a sequential model, therefore, the upper level may represent decision-makers whose decisions lead to some reaction within a particular market or social entity, which corresponds to the lower level of the problem.

Transportation planning is also a typical domain in which examples of such hierarchical structures appear: the upper level corresponds to the network operator seeking to improve the performance of the network, and the lower level corresponds to network users making their travel choices (Labbé and Violin, 2013).

In simple words this is where the values of the decision variables of the first problem influence the optimal solution of the second problem and vice versa. In game theory, an equivalent problem is known as the Stackelberg game.

The general bi-level problem can be formulated as;

$$\min_{x,y} f(x, y),$$

s.t \( (x, y) \in X, \)

$$y \in S(x),$$

where \( S(x) = \arg\min_y g(x, y), \)
s. t. \((x, y) \in Y\)

Where \(x\) and \(y\) denote the decision variables and \(X\) and \(Y\) denote the solutions space for leader and the follower respectively. \(f\) and \(g\) are objective functions.

When there are multiple objectives in the upper level, the problem can be mathematically formulated as follows.

\[
\min_u F(u, v(u)) = \begin{cases} 
F_1(u, v(u)) \\
F_2(u, v(u)) \\
\cdots \cdots \cdots \\
F_k(u, v(u)) 
\end{cases}
\]

subjected to \(G(u, v(u)) \leq 0\)

where \(v(u)\) is implicitly defined by \(\min_v f(u, v)\)

subjected to \(g(u, v(u)) \leq 0\)

Where;

- \(F(u, v(u))\) - Objective function vector of the upper level
- \(u\) - Decision vector of the upper level
- \(G\) - Constraint set of the upper level
- \(f(u, v)\) - Objective function vector of the lower level
- \(v\) - Decision vector of the lower level
- \(g\) - Constraint set of the lower level

From a computational perspective, bi-level problems are difficult to solve and considered as NP-hard problems. Therefore, various algorithms are used to find an optimal solution, which is discussed under the optimization sub-section presented later in this chapter.

The optimal toll design problem has been formulated as a bi-level problem as shown in Figure 3.2. On the upper level, policymakers or the government determines the tolls (for multi-class vehicles) on a set of links, while on the lower level, travelers react to these
toll levels either by changing their route choices or changing the mode of travel or abandoning the trip. This hierarchical relationship exists between two autonomous, possibly conflicting decision makers. This condition is similar to the Stackelberg game (leader-follower) in economics. However, it is important to note that leaders cannot control followers or their decision making, but they can only influence them by setting the toll price. Therefore, once the toll prices are set, it is all users’ decision to choose which route should be taken to a given destination.

![Figure 0.2: Problem Structure](image)

The government makes two decisions with respect to a given scenario. The first decision is concerning the road network for trucks and the second decision is the toll charges for multiple classes of vehicles considering the heterogeneity of freight vehicles. It is the
government’s responsibility to maximize the welfare of residents and the public in terms of minimizing environmental and social costs. In addition, the government is also responsible for protecting road investors (under PPPs) and this is considered an objective in the upper-level as shown in Figure 3.2. When the government tries to minimize the total cost of transportation, which is required for a sustainable future, the revenue from toll charges tends to decline. This conflict is always there when multi-stakeholder multi-objective problems are concerned and therefore finding an optimized solution is not an easy task.

Alternatively, the revenue from toll charges can be considered as a constraint where the minimum level return can be measured using Internal Rate of Return (IRR) to protect road investors incurring a loss from the PPP. As a result, the government would look at this problem with a broader perspective and thus all stakeholder’s concerns should be seriously considered when providing a suitable solution aiming at sustainable transportation. A biased result would not succeed in the long run and there is a high possibility of a system failure.

Apart from the government, road investors and users, the other key stakeholders in this system are the residents and the general public. The general public has no direct involvement in this system but indirectly suffer from decisions made by users followed by the investors’ toll-setting decisions. In brief, toll avoidance by trucks has generated environmental and social impacts which have a great effect on residents, other road users, and the public. The unfavorable conditions are aggravated by rising toll prices as experienced in Melbourne and other cities. Therefore, externalities produced by vehicles (especially from trucks) are also a concern of the government. At the lower level, decisions are made by individuals looking to minimize their costs. However, the government, on the other hand, would like to lower the overall cost of transportation (which may disturb the user equilibrium). As a result, user costs have been considered as the first objective of the upper-level (government) in this problem formulation and social costs which consist of congestion costs, crash costs, and infrastructure costs, are considered as the second objective. Emission costs and noise costs are considered to be environmental costs and are set as the third objective in the upper-level.
The hierarchical structure shown above does not make any significant change to the bi-level formulation of the problem, but multiple objectives have been added. Therefore, this can still be considered as a bi-level problem with multiple objectives. The lower-level problem can be considered as a multi-class user equilibrium problem which has been solved in the literature as a network design problem (NDP) for various networks. In this study, multi-class user equilibrium was carried out using an extended version of the Frank-Wolfe algorithm (see Equation 3.30) for the given network under given toll conditions to determine the traffic flow on each link. For more information readers may refer to Sheffi, (1984), Li et al., (2008) and INRO Consultants Inc., (2017).

Since the upper level is an optimization problem and the lower level is an equilibrium problem this design problem can be considered as a mathematical program with equilibrium constraints (MPEC). The MPEC is a special case of bi-level programming problem and is difficult to solve due to their intrinsic non-convexity and presence of non-linear multiple objectives and constraints. Therefore, a heuristic solution procedure, more preferably a metaheuristic algorithm is required to solve such an NP-hard problem. Thus, the Non-dominated Sorting Genetic Algorithm II (NSGA II) has been used to solve this optimization problem (Deb, 2002; Deb et al., 2002; Srinivas and Deb, 1994).

### 3.3.2 Mathematical formulation

As mentioned above this mathematical problem has two levels, upper and lower levels. The upper level describes the role of the policymaker, which is usually the government, who tries to minimize one or multiple objectives as per the given conditions. The following formulation is explicitly used for optimizing 3 main objectives considering all key stakeholders (single objective formulation is shown in Chapter 8). The first objective is to minimize total user costs (including toll costs) as depicted in equation (3.1). The second objective is to minimize social costs and the third objective is to minimize environmental costs as depicted in equations (3.2) and (3.3), respectively. The return from toll charges is not considered as an objective at the upper level but considered as a constraint. The mathematical formulation is as follows.
The upper-level problem is formulated as:

\[
\begin{align*}
\min & \left[ \sum_{a \in A} \sum_{m \in M} [V C_a^m d_a + VT_a^m t_a] * x_a^m + \sum_{a \in A} \sum_{m \in M} [V C_a^m d_a + VT_a^m t_a + T_a^m] * x_a^m \right] \\
\min & \sum_{a \in A} \sum_{m \in M} [\rho A C_a^m + \sigma C C_a^m + \tau I C_a^m] * d_a * x_a^m \\
\min & \sum_{a \in A} \sum_{m \in M} [\varphi E M_a^m + \omega N C_a^m] * d_a * x_a^m
\end{align*}
\]

(3.1) (3.2) (3.3)

where

- \( a \): Road link \( a \in A \cup \overline{A} \), where \( A \) denotes set of un-toll links and \( \overline{A} \) denotes toll links
- \( m \): Vehicle type, \( m \in M \), where \( M \) denotes set of multi-class vehicles
- \( x_a^m \): Traffic flow on the link \( a \) w.r.t vehicle type, \( a \in A \cup \overline{A}, m \in M \) (veh/hr)
- \( T_a^m \): Toll charge for each vehicle type for the given link \( a \), \( a \in \overline{A}, m \in M \) (A$/km)
- \( t_a \): Travel time on the link \( a \), \( \forall a \in A \cup \overline{A} \) (minutes)
- \( d_a \): The distance of link \( a \), \( \forall a \in A \cup \overline{A} \) (meters)
- \( VT^m \): Value of operating time for vehicle type, \( m \in M \) (A$/min)
- \( V C_a^m \): Vehicle operating cost vector with speed, road type, multi-class, \( a \in A \cup \overline{A}, m \in M \) (A$/vkm)
- \( AC_a^m \): Accident cost vector with road type for a given link \( a \), \( a \in A \cup \overline{A}, m \in M \) (A$/vkm)
- \( CC_a^m \): Congestion cost vector with v/c ratio and road type \( a \), \( a \in A \cup \overline{A}, m \in M \) (A$/vkm)
- \( IC_a^m \): Infrastructure cost vector for road type for given link \( a \), \( a \in A \cup \overline{A}, m \in M \) (A$/vkm)
- \( NC_a^m \): Noise cost vector with a time of day and traffic condition (v/c), \( a \in A \cup \overline{A}, m \in M \) (A$/vkm)
- \( EM_a^m \): Emission cost for given vehicle type, on a given link \( a \), \( a \in A \cup \overline{A}, m \in M \) (A$/vkm)
- \( \rho, \sigma, \tau \): Weights at which social cost is implied (all assumed as 1)
Methodology

\( \varphi, \omega \) : Weights at which environmental cost is implied (all assumed as 1)

\( TR \) : Toll Revenue (A$)

\( TR_L \) : The lower limit of the Toll Revenue accepted by the Investor (A$)

\( u_{am} \) : The upper limit of the toll charge for each vehicle type on each link, \( a \in A, m \in M \) (A$)

\( l_{am} \) : The lower limit of the toll charge for each vehicle type on each link, \( a \in A, m \in M \) (A$)

\( UL_{TR} \) : The upper limit for the toll revenue (A$)

\( LL_{TR} \) : The lower limit for the toll revenue (A$)

\( \gamma, \beta \) : Integers, 0 or 1

\( v_a \) : Average speed on link \( a \) (km/hr)

subject to the following constraints:

\[
x_{am} \geq 0, \quad \forall \ a \in A \cup \overline{A}, \quad m \in M \tag{3.4}
\]

\[
u_{am} \geq T_{am} \geq l_{am} \quad \forall \ a \in A \cup \overline{A}, \quad m \in M \tag{3.5}
\]

\[
d_a \geq 0, \quad \forall \ a \in A \cup \overline{A} \tag{3.6}
\]

\[
t_a \geq 0, \quad \forall \ a \in A \cup \overline{A} \tag{3.7}
\]

\[
UL_{TR} \geq \sum_{a \in A} \sum_{m \in M} T_{am} x_{am} \geq LL_{TR} \quad \text{Based on a pre-defined IRR} \tag{3.8}
\]

\[
VC_{am} \geq 0, \quad \forall \ a \in A \cup \overline{A}, \quad m \in M \tag{3.9}
\]

\[
VT_{am} \geq 0, \quad \forall \ a \in A \cup \overline{A}, \quad m \in M \tag{3.10}
\]

\[
AC_{am} \geq 0, \quad \forall \ a \in A \cup \overline{A}, \quad m \in M \tag{3.11}
\]

\[
CC_{am} \geq 0, \quad \forall \ a \in A \cup \overline{A}, \quad m \in M \tag{3.12}
\]

\[
IC_{am} \geq 0, \quad \forall \ a \in A \cup \overline{A}, \quad m \in M \tag{3.13}
\]

\[
EM_{am} \geq 0, \quad \forall \ a \in A \cup \overline{A}, \quad m \in M \tag{3.14}
\]

\[
NC_{am} \geq 0, \quad \forall \ a \in A \cup \overline{A}, \quad m \in M \tag{3.15}
\]

\[
1 \geq \rho \geq 0 \tag{3.16}
\]

\[
1 \geq \sigma \geq 0 \tag{3.17}
\]

\[
1 \geq \tau \geq 0 \tag{3.18}
\]

\[
1 \geq \varphi \geq 0 \tag{3.19}
\]
Methodology

\[ 1 \geq \omega \geq 0 \quad (3.20) \]

\[ \sum_{a} \sum_{m} AC_{a}^{m} x_{d}^{m} d_{a} \geq 0 \quad (3.21) \]

\[ \sum_{a} \sum_{m} CC_{a}^{m} x_{d}^{m} \geq 0 \quad (3.22) \]

\[ \sum_{a} \sum_{m} IC_{a} x_{d} d_{a} \geq 0 \quad (3.23) \]

\[ \sum_{a} \sum_{m} \left[ (a_{2}s_{a} + a_{1}s_{a} + a_{0})\gamma \right. \]
\[ + \left. \left( b_{0} + \frac{b_{1}}{s_{a}} \right) \beta \right] x_{d}^{m} d_{a} \geq 0 \quad (3.24) \]

\[ \sum_{a} \sum_{m} NC_{a}^{m} x_{d}^{m} d_{a} \geq 0 \quad (3.25) \]

Equations (3.1)- (3.3) denote the objective functions for the upper-level. Equation (3.1) denotes the objective function to minimize total user costs on the network considering both tolled links (roads) and non-tolled links. Equation (3.2) calculates the minimum total social costs and equation (3.3) calculates the minimum total environmental costs in the entire network. Equations (3.4) to (3.25) denote the constraints for the objective functions (3.1) to (3.3) and are explained as follows. Equation (3.4) denotes the non-negativity of traffic flows whereas equation (3.5) denotes the boundaries defined for individual toll charges. Again, equations (3.6) and (3.7) denote the non-negativity of link distances and link travel times, respectively. Equation (3.8) denotes the upper bound and lower bound for toll revenue based on a pre-determined Internal Rate of Return (IRR) value. Equations (3.9) to (3.15) denote the non-negativity of different cost elements and equations (3.16) to (3.20) denote the upper and lower bounds for the coefficient used for externalities. Equations (3.21) to (3.25) denote the non-negativity of the different externalities calculated.

All weights given for the social and environmental factors \((\rho, \sigma, \tau, \phi, \omega)\) will be considered as one for the default case but can be determined exogenously or endogenously. Exogenous determination of weights can be done based on values available to policy makers from other policies available or from theoretical knowledge.
Otherwise, these values can be determined from the model itself (endogenously) by considering such weights as variables and running the optimisation process. A Pareto-optimal solution set could be obtained for these weightings for a given scenario and the best can be selected by policy makers.

Since all three objectives considered in this study are measured in dollar terms it is possible to convert the multi-objective optimization problem into a single objective optimization problem using the weighted sum method to combine three objective functions into one function. However, the conversion will loss important trade-off information and lead to insufficient solutions (Wu et al., 2013). In addition, the conversion will lead to a single solution, reducing the flexibility in the decision-making process. Therefore, a genuine multi-objective approach is used in this study to understand the nature of the trade-offs among user costs, environmental costs, and social costs.

The lower limit of the toll revenue \( LL_{TR} \) as well as the upper limit \( UL_{TR} \) can be determined based on the terms and conditions of the PPP contract made with the government. However, the number of operational years given for the investor is another critical parameter when deciding toll charges (Odeck, 2017). Therefore, the following equation needs to be considered in relation to equation (3.8) above. This mathematical formulation considers the life cycle costs and benefits of the infrastructure development and the IRR is calculated as the rate at which the net present toll revenue \( NPT_R \) is equal to zero.

\[
NPTL = \sum_{y \in Y} \left( \int_{h-1}^{h} \left\{ \sum_{a \in A} \sum_{m \in M} [T_a^m - IC_a^m] * x_a^m * d_a * d_t \right\} - FM_a(C_a) \right) \left( 1 + r \right)^y - \left\langle IC_a(C_a) \right\rangle \tag{3.26}
\]

\[
s.t.
\]
\[
r \geq 0 \tag{3.27}
\]
\[
Y \geq 0, \text{ and integer} \tag{3.28}
\]
\[
h \geq 1, \text{ and integer} \tag{3.29}
\]
where

\[ C_a : \text{The capacity of road link } a, \forall a \in A \cup \bar{A} \text{ (veh/hour)} \]

\[ FM_a(C_a) : \text{Fixed maintenance cost per year as a function of link capacity} \]

\[ IC_a(C_a) : \text{Infrastructure capital cost as a function of link capacity} \]

\[ Y : \text{Number of years given (in PPP) for toll operation, } y \in Y \text{ and integer} \]

\[ r : \text{Discount rate (a non-negative real number)} \]

\[ h : \text{Time in hours per year (an integer)} \]

Equation (3.26) determines the total profits earned by the investor from this project considering the lifespan of the project. All relevant costs and benefits are considered and discounted appropriately in order to arrive at the net present value of the toll revenue (NPTR). This equation is used to determine the Internal Rate of Return (IRR) mentioned above. Equations (3.27) to (3.29) ensure the non-negativity of variables.

The lower-level problem is formulated as follows considering multi-class traffic:

\[
\min_{x} z(x) = \sum_{a} \int_{0}^{X_a} t_{a}(x) \, dx + \sum_{a} \sum_{m} X_{a}^{m} b_{a}^{m} \tag{3.30}
\]

subject to:

\[
\sum_{k} f_{k}^{rs} = q_{rs} \quad \forall \ r, s \tag{3.31}
\]

\[ f_{k}^{rs} > 0 \quad \forall \ k, r, s \tag{3.32} \]

\[ x_{a} = \sum_{r} \sum_{s} \sum_{k} f_{k}^{rs} \delta_{a,k}^{rs} \quad \forall \ a \in A \tag{3.33} \]

\[ b_{a}^{m} \geq 0 \quad \forall \ a \in A, m \in M \tag{3.34} \]

Where,

\[ b_{a}^{m} : \text{Bias w.r.t. vehicle type and road type, } a \in A \cup \bar{A}, m \in M \]

\[ q_{rs} : \text{Trip rate between origin } r \text{ and destination } s \]

\[ f_{k}^{rs} : \text{Traffic flow on path } k \text{ from origin } r \text{ to destination } s, \ k \in K_{rs} \]

\[ \delta_{a,k}^{rs} = 1 \text{ if link } a \text{ is part of path } k \text{ connecting O-D pair } r-s, \text{ and } \delta_{a,k}^{rs} = 0 \text{ otherwise} \]
Equation (3.30), which is the objective function for the lower-level, minimizes the travel times/costs of users using different paths including multi-class tolls. Equation (3.31) balances the demand for vehicles on each path and equation (3.32) denotes the non-negativity of vehicle flows on paths. Equation (3.33) balances all link flows with path flows and equation (3.34) denotes the non-negativity of the ‘b’ value.

The traffic flow on link $a \in A \cup A$ is denoted by $x_a$ and the link travel time is calculated based on the Bureau of Public Roads (BPR) travel time function given in equation (3.35).

$$t_a = t_0 \left[ 1 + \alpha \left( \frac{x_a}{c_a} \right)^\beta \right]$$ (3.35)

### 3.3.3 Sub-models for the upper level

In the upper level as shown in Figure 3.2, there is mainly one sub-model that provides the additional information required to make the decisions made at the upper level. This sub-model is known as the freight vehicles cost model, which calculates the direct costs and indirect costs (externalities) of the freight vehicles under various scenarios. In addition, the answers to some questions in Part A of the survey have been used to shape this bi-level model. More details about the input from the survey are given in Chapter 6.

The aim of the truck cost model development is to identify different cost components and calculate the most reasonable values for Australia by combining the historical data available. A comprehensive literature review was carried out in order to find the best values for various sections and most appropriate numbers are produced. However, with evolving technology and developments in infrastructure, these numbers are likely to vary over time. Therefore, in the future, if these numbers are continued to be used, a decent upgrade is essential to fine-tune these with key changes. Figure 3.3 given below depicts the basic flowchart used to calculate the different cost values under truck costs and detailed information is provided in Chapter 4.
3.3.4 Sub-models for the lower level

3.3.4.1 Traffic assignment techniques

Traffic assignment models have been used in the world for decades by transport planners to forecast traffic flows and travel times in order to find solutions for present and future matters. Traffic assignment models can be primarily two types, spatial and temporal. Ranging from static to dynamic models there exist a wide range of traffic assignment models proposed in the literature considering the temporal factor. Based on the spatial factor, models consider free-flow conditions, congestion with queuing and spillback and Figure 3.4 below demonstrates these different options.

However, none of the models seems to be ideally representing the true situation where there are many assumptions made in models to simplify the complexity and most of the assumptions are implicit. As a result, deeper insights into these assumptions allow a better understanding of the capabilities of each model and the conditions under which models can be applied.
Assumptions are commonly made to restrict variability in traffic flows and related parameters and some of the common variables are as follows.

- Single user or multi-class vehicles
- First order effects-time, capacity, LOS
- Second order effects- capacity drop, stop-and-go waves, hysteresis
- Elastic travel demand
- Route choice variables- travel time, length, road type, land use types, environment, etc.
- Route choice- perfect or imperfect information, rational behavior, bounded rational
- Departure time choice-rigid vs flexible (flexibility may depend on congestion, time of the day, etc.)
- Mode choice- the mode will be selected under prevailing conditions such as cost, the time taken to complete the intended journey, linked trips, the number of people, accessibility, etc.

Usually, travel time or travel distance (shortest path) is considered for traffic assignment problems in models but minimum cost is rarely used. In fact, “total cost” as a basis of
the trip assignment is in limited use, which is crucial in freight industry decision making as described in other sections of this thesis.

Apart from the various assumptions made, there are two preliminary objective functions that are used in traffic assignment. The most common one is the User Equilibrium (UE) where each user enjoys the same travel time on different routes between same OD pair and the second method is where System Optimisation (SO) is achieved in the network. In this method, the overall network is considered than optimizing individuals benefit, thus optimum conditions for the system are achieved, whereas some users spend more and some users spend high travel times (or cost) based on the route they used in the same OD pair.

However, SO conditions cannot be achieved in a real-world scenario, especially in the freight industry because individual transport cost (minimization) is crucial for them to remain in the industry. As a result, this study was only limited to UE conditions, where each freight vehicle is considered as a typical user with rational behavior.

3.3.4.1.1 User equilibrium

The famous UE principle was developed based on (Wardrop, 1952) first principle, which was extended to Stochastic-User-Equilibrium (SUE) by (Daganzo and Sheffi, 1977) which accounts for uncertainty in travel cost. UE models are widely used in congested traffic networks but perform weakly in less congested, inter-urban networks. Stochastic methods are more suitable for lightly congested networks, typically inter-urban networks (Maher and Hughes, 1997). Since then many studies were carried out in academia looking at various aspects of UE and SUE (Huang and Lam, 2002; Lam et al., 1999). Many algorithms were developed to solve these problems including methods of successive average (MSA) (Bell and Cassir, 2002; Damberg et al., 1996; Davis, 1994; Dial, 2006). Simple multinomial logit (MNL) or multinomial probit (MNP) models were used firstly to solve route choice problems (Prashker and Bekhor, 2004) and later many discrete models were used to find route choices such as C-logit, path-size logit (PSL), paired combinatorial logit (PCL), cross-nested logit (CNL) and logit kernel (LK) models (Prashker and Bekhor, 2004).
3.3.4.1.2 System optimal

System Optimal traffic network analysis has been carried out focusing on many aspects of transportation, especially the travel cost (Jahn et al., 2005; Muñoz and Laval, 2006; Peeta and Mahmassani, 1995). System optimum dynamic traffic assignment problems are difficult to solve compared to a static network. Kanafani and Al-Deek (1991) developed a simple model for route guidance using system optimal assignment and Yang (1999) studied how tolls can be optimized considering SO.

Since this study is mainly focused on solving a toll optimization problem but not a traffic assignment problem, the most common and widely used UE technique was used. Since UE performs well in congested conditions and the requirement to find quick solutions, supported the decision to use UE to assign traffic in the network. In addition, to make this traffic assignment problem as simple as possible (since the focus of the study is elsewhere) static demand conditions were used.

3.3.4.1.3 Multi-class traffic assignment

For many decades traffic flows with a single class have been studied and with the introduction of multi-class forms by Dafermos (1972), a new era of traffic studies started where many researchers used it in different ways to solve various problems (Bagnerini and Rascle, 2003; Bliemer and Bovy, 2003; Herty et al., 2006; Li and CHEN, 2008; Wong and Wong, 2002). Consideration of multi-classes is important in traffic studies mainly due to heterogeneity nature of commuters, where different VOT exist between users. Multi-class, multi-criterion traffic equilibrium was used to find user optimal conditions and system optimal conditions (Yang and Huang, 2004a), with elastic demands (Nagurney, 2000), using advanced user information system (Huang and Li, 2007), and to evaluate efficiency of congestion pricing (Han and Yang, 2008). Holguín-Veras and Cetin, (2009) found an optimum toll for multi-class traffic whereas Yang and Zhang, (2002) solved toll problems with social and spatial equity constraints for multi-classes.

In this study each vehicle type has its separate toll charge, operational costs and emissions, single vehicle class traffic assignment is not appropriate and thus multi-class traffic assignment was used. However, a simpler form of the multi-class assignment developed by the INRO Consultants Inc., (2017) was used. For this assignment, it is
assumed that the cost (given in minutes) of link $a$ perceived by a user of class $m$ can be written as:

$$s_a^m(x_a) = t_a(x_a) + b_a^m \quad a \in A \cup \overline{A}, \quad m \in M \quad (3.36)$$

$$b_a^m \geq 0 \quad a \in A \cup \overline{A}, \quad m \in M \quad (3.37)$$

where

- $b_a^m$ : Biasness w.r.t vehicle type and road type, $a \in A \cup \overline{A}, m \in M$
- $s_a^m$ : New friction factor for traffic assignment (minutes)

Equation (3.36) defines the biasness used in multi-class traffic assignment and equation (3.37) denotes the non-negativity of such biasness for all vehicle types. Therefore, equation (3.36) can be re-expressed as:

$$\min z(x) = \sum_a \int_0^{x_a} t_a(x) \, dx + \sum_a \sum_m x_a^m b_a^m \quad (3.38)$$

This formulation implies that different vehicle classes are subjected to the same congestion effect estimated based on the total volume of the link, but each user class perceives a different constant bias $b_a^m$. In other words, this bias value has been used in this study to differentiate between different vehicle categories with respect to their route selection when multi-class toll charges are involved. The response (friction) to a different toll charge by a vehicle category has been used as input for this model via the bias value as explained in the next section.

### 3.3.4.2 Toll charges and the bias value

When a toll is involved, the toll elasticity will determine whether or not a user will choose the toll road at a given toll charge. Different vehicle types would respond differently to various toll charges and the decision is determined by several parameters. Some studies (Han and Yang, 2008; Yang and Huang, 2004b) and commercial software like VISUM (PTV AG, 2018), EMME (INRO Consultants Inc., 2017) assume that vehicle response to tolls is a matter of monetary value for time (time-saving). As a result, the time value of money has been used to determine the various responses for multi-class vehicles, which is a linear relationship with time (bias) and money (tolls). However,
beyond the monetary implication, there are other qualitative factors behind this toll-elasticity decision which may hinder the linear relationship. Hesitant to experience stop-go conditions on a highway, especially for cars on a business trip, is another major contributing factor determining the likelihood of choosing a toll road at a high toll level by a vehicle user. Car users are usually not driving their cars as part of their occupation, but to satisfy their own transportation needs. Whereas for freight vehicle drivers, driving is their job and they do it on a daily basis to make a living. Thus, the purpose of driving is also a determining factor for toll-elasticity calculation. In addition, it was found that most freight vehicles find it difficult to either transfer the toll cost (to receiver/supplier) or to absorb the cost due to present competition (Holguín-Veras, 2011). In such circumstances, the availability of alternative roads is a factor in encouraging toll avoidance (Matas and Raymond, 2003).

In order to find out what factors are influencing the decision to use toll roads a discrete choice experiment (DCE) was carried out as explained below.

This discrete choice experiment was carried out to investigate the freight driver’s response towards choosing toll roads over highway. The travel time, travel distance and toll charges are the three attributes used in this experiment with different levels for each attribute. More details about the attributes, attribute levels and survey method is explained in Chapter 6.

The utility of freight driver choosing a toll road over highway can be specified as;

$$U^i = V^i + \varepsilon^i$$  \hspace{1cm} (3.39)

Where;

$V^i$: the deterministic component of the utility

$\varepsilon^i$: the random component of the utility function for individual $i$

Different models deal differently with the error or random component $\varepsilon^i$. 

**Methodology**

**Logit Model** - widely used discrete choice model. Assumed that $\varepsilon_{ni}$ is iid extreme value for all $i$. The critical part of the assumption is that the unobserved factors are uncorrelated over alternatives, as well as having the same variance for all alternatives.

**Generalized Extreme Value Models (GEV)** - are based on the generalisation of the extreme value distribution. This allows correlation in unobserved factors over alternatives and collapses to the logit model when this correlation is zero. (GEV model places the alternatives into several groups called nests)

**Probit** - assumes that unobserved factors are distributed jointly normal. The flexibility of the probit model handling correlations over alternatives and time is its main advantage. However, the problem arises when it assumes unobserved component is normal distributed and where such case does not exist.

**Mixed Logit** - this allows unobserved factor to follow any distribution and it can be divided into parts where one part follows iid extreme value where the other part follows any distribution, including non-normal distributions.

From the past studies it can be seen that the multinomial logit (MNL) model has been used for many transportation applications. However, despite the easy implementation, it was found that MNL models are unable to capture the random taste heterogeneity across decision makers (Hess et al., 2005). Since mixed multinomial logit (MMNL) models are capable of estimating such arbitrary behaviour, researchers have recently begun to use MMNL models extensively (Hess et al., 2005). Thus, the MMNL model was used in this analysis as well.

Therefore, by considering the above attributes and choice sets developed, the deterministic component of the model can be written as;

$$V^i = \beta_{TT}x_{TT}^i + \beta_{TD}x_{TD}^i + \beta_{TL}x_{TL}^i$$

(3.40)

Where;

$x_{TT}^i, x_{TD}^i, x_{TL}^i$: observable components for travel time (TT) in minutes, travel distance (TL) in kilometres and toll charge (TL) in A\.}
\( \beta_{TT}, \beta_{TD}, \beta_{TL} \): Are respective coefficients.

From the utility theory the following values for travel time and travel distance can be obtained.

\[
v_{TT} = \frac{\beta_{TT}}{\beta_{TL}} \quad (3.41)
\]

\[
v_{TD} = \frac{\beta_{TD}}{\beta_{TL}} \quad (3.42)
\]

Where

\( v_{TT} \): Value of travel time (A$/min)

\( v_{TD} \): Value of travel distance (A$/km)

Based on the results obtained from the DCE (presented in Chapter 6) it can be concluded that travel time is the determinant factor for toll charges, not the distance. Considering the behavioral response provided in the literature (Gomez et al., 2017) and considering the above facts a graph was developed for this study assuming that vehicles would respond to tolls in a non-linear manner represented by bias values, as shown in Figure 3.5. The bias values are used in equation (3.30).

![Figure 0.5: Toll charge vs expected bias values](image-url)
In Figure 3.5, it was assumed that large trucks would respond more to toll increases than cars, because it is has been found in previous studies that car drivers value their travel time more compared to truck drivers due to involvement of passengers and various trip attributes (Hensher et al., 1990; Hensher and Goodwin, 2004). Consequently, car drivers are more likely to keep using the toll road with higher toll charges, whereas large trucks will more likely to avoid toll roads when toll charges increase (Holguín-Veras, 2011).

3.3.5 Optimisation

The evaluation process will be mainly focused on developing a toll structure and estimating impacts based on various objectives. It could be a single objective optimization or multi-objective optimization based on how the scenario is defined. For any scenario, the flow chart shown in Figure 3.6 depicts the basic steps. This exercise will be helpful to achieve an optimum toll condition for a given objective(s) optimized with minimum impacts.
For single objective optimization, Genetic Algorithms were used in this study and for multi-objective optimization NSGA II was used.

### 3.3.5.1 Optimisation techniques

The fundamental properties of metaheuristic algorithms are that they follow certain strategies taken from nature, social culture, biology or laws of physics that direct the search process. Their goal is to efficiently explore the search space using these governing mechanisms and to find near optimal solutions if not a global optimum. The strategies used have some features to avoid getting trapped in confined areas of the search space.

Metaheuristic techniques are approximate techniques and there is no mathematical proof that the optimum solution obtained is the global one. However, they are not problem specific and proven to be very efficient and robust in obtaining the solution of
practical engineering design optimization problems with both continuous and discrete
design variables. The mechanisms employed in search of an optimum solution in these
techniques simulate the natural phenomena such as survival of the fittest, immune
system, swarm intelligence, the cooling process of molten metals through annealing,
social culture, music improvisation, big bang-big crunch theory into a numerical
algorithm (Saka and Dogan, 2012).

The early metaheuristic methods that were very widely applied in engineering design
were evolutionary algorithms and among these were the genetic algorithms. This was
followed by simulated annealing, immune algorithm, tabu search method, and memetic
algorithm. Between 1990 to 2000 ant colony optimization, particle swarm optimization
and differential evolution were published in the literature.

In the history of solving various transportation and related problems, different
algorithms are used to achieve optimization in various aspects such as network, traffic,
toll charges, travel time, travel cost and especially for vehicle routing problems (Pellazar,
1994; Shepherd and Sumalee, 2004). Among many metaheuristic methods Genetic
Algorithm (GA), Tabu Search (TS), Particle Swarm Optimisation (PSO) Algorithm are few
popular algorithms used in transportation studies. These heuristic search techniques are
found to be more effective than gradient techniques in finding the global minimum
(Yildiz and Solanki, 2011).

Genetic algorithms (GA) one of the popular algorithms used in transport studies, was
introduced in the mid-1970s by John Holland and his colleagues and students at the
University of Michigan. GA are inspired by the principles of genetics and evolution and
mimics the reproduction behavior observed in biological populations. GA employ the
principle of “survival of the fittest” in its search process to select and generate
individuals that are adapted to their environment. Therefore, over a number of
iterations, desirable traits will evolve and remain in the genome composition of the
population over traits with weaker undesirable characteristics. GA are well suited to and
have been extensively applied to solve complex design optimization problems because
they can handle both discrete and continuous variables, and nonlinear objectives and
constraint functions without requiring gradient information (Hassan et al., 2005). GA
have been used in transport studies to solve shortest path problems, toll optimization, traffic signal optimization, and routing, trip scheduling, etc. (Ahn and Ramakrishna, 2002a; Shepherd and Sumalee, 2004; Teklu et al., 2007; Wren and Wren, 1995).

It is known that the PSO algorithm is more efficient than genetic algorithms (GA) at exploring the solution space, but it does not guarantee the global optimum as other evolutionary methods (Yildiz and Solanki, 2011). This algorithm was used in solving many transport problems, among many including, traveling salesman problem (Shi et al., 2007), shortest path problem (Mohemmed et al., 2008), vehicle routing problems (Belmecheri et al., 2012; Goksal et al., 2013), highway alignment optimization (Shafahi and Bagherian, 2013) and crash worthiness optimization (Yildiz and Solanki, 2011).

3.3.5.2 Why GA?

Global optimization has found an increasing number of applications not only in engineering but also across applied sciences, science and economics. Global optimization addresses the computation and characterization of global solutions to non-convex continuous, mixed-integer, differential-algebraic, bi-level, and non-factorable problems (Floudas and Gounaris, 2009). When problems are complex, it has become difficult to find an exact solution and thus heuristic methods became more popular. Heuristic methods allow a good solution (near optimum) to be found within a reasonable computation-time and with reasonable use of memory without any loss of subtle non-linear characteristics of the model and without any requirement of complex derivatives or careful choice of initial values (Geem et al., 2001). These classical heuristics and metaheuristics developed mostly a few decades ago and last decade respectively (Laporte et al., 2000).

In general, search and optimization techniques can be classified as, enumerative, deterministic and stochastic (random) (Coello et al., 2007). Since real-world engineering optimization problems are multi-objective, NP-hard, non-convex with non-linear constraints, which cannot be solved using enumerative and deterministic search techniques, there is a necessity for further advanced optimization techniques to be developed.
Metaheuristic algorithms, known as a better version of heuristic algorithms are extensively used to solve large sized optimization problems with exponential search space which require an advanced search to find the global optimum. Gendreau and Potvin, (2010) have introduced a list of desirable properties for metaheuristics. Simplicity, precision, coherence, effectiveness, efficiency, robustness, user-friendliness, innovation, generality, interactivity, and multiplicity are those properties. Metaheuristic algorithms with a population-based framework have shown satisfactory capabilities to handle high dimension optimization problems (Beheshti and Shamsuddin, 2013) and Genetic Algorithms are one of the popular metaheuristic algorithm among the list.

Population-based algorithms are popular for solving complex optimization problems over traditional search where population-based algorithms have proven that they can generate a number of near global solutions when a termination criterion is met (Yildiz and Solanki, 2011). On the other hand, traditional optimization methods are time-consuming in solving non-linear and complex optimization problems, they may not be used in finding global optimum solutions due to inefficiency (Yildiz and Solanki, 2011). Tabu Search, Simulated Annealing, Iterated Local Search, Variable Neighbourhood Search, Greedy Randomized Adaptive Search Procedure are such few single point search commonly found meta-heuristic algorithms.

Genetic Algorithms (GA), are often referred to as evolutionary algorithms, resembling natural selection and reproduction processes governed by rules that assure the survival of the fittest in large populations. There intuitiveness, ease of implementation, and the ability to effectively solve highly non-linear, mixed integer optimization problems that are typical of complex engineering systems (Gendreau and Potvin, 2010; Hassan et al., 2005) has enabled the high usage of them in solving real-world problems. Furthermore, GA are well suited to and have been extensively applied to solve complex design optimization problems because it can handle both discrete and continuous variables, and nonlinear objective and constraint functions without requiring gradient information (Hassan et al., 2005). In addition, GA are characterized by a parallel search of the solution space compared to point-by-point search by the conventional optimization techniques (Youssef et al., 2001) and able to provide a population of solutions which clearly shows the trade-offs. Therefore, the motivation for using GA is due to globality, parallelism,
and robustness (Yin, 2000). In addition, GAs are simple yet powerful in their search for improvement and are not fundamentally limited by restrictive assumptions about the search space (assumptions concerning continuity, the existence of derivatives, and other matters). As Goldberg (1989) stated, GAs are different from more normal optimization and search procedures in four ways.

However, none of the meta-heuristic algorithms are able to present a higher performance than others in solving all problems. Also, existing algorithms suffer from some drawbacks such as slow convergences rates, trapping into local optima, having complex operators, long computational time, need to tune many parameters and designed for only real or binary search space (Beheshti and Shamsuddin, 2013). In that regard, GA also have a few main drawbacks. Lack of good local search ability, premature convergence (Beheshti and Shamsuddin, 2013; Rıza Yıldız, 2009) and producing unpredictable results (sometimes) need to be handled carefully when using GA to solve complex problems.

GA’s (along with Monte Carlo techniques and simulated annealing) belong to a small but growing class of so-called global optimizers which are stochastic in nature and, therefore, less prone to converge to a weak local optimum than deterministic optimization methods (DOM’s). GA’s differ from most traditional optimization methods in two ways. First, they do not necessarily operate directly on the design parameters, and second, they simultaneously optimize entire populations of designs at once, not a single design at a time. Small modifications to the algorithm can lead to advanced GA techniques which are capable of solving more complex problems, optimize faster or more globally (dominance, community structure, sharing, or knowledge-based operators). Often engineers face the task of satisfying conflicting goals in a single design. The problem then is not finding a design that is optimal with respect to a single design goal, but a design which makes trade-offs between conflicting goals. Whenever this occurs, Multi-objective optimization technique is required. GA’s are ideal for such problems because their reliance on a population allows them to return a wide variety of designs representing optimal trade-offs.
3.3.5.3 Genetic Algorithm (GA)

Genetic algorithms (GAs) are an adaptive heuristic search mechanism based on the ideas of natural selection and genetics (Goldberg and Richardson, 1987; Weile and Michielssen, 1997). GAs have been used to solve many complex engineering problems, such as heat exchanger network synthesis optimization in industrial plants (Ravagnani et al., 2005), the unit commitment problem in power systems and the integrated inventory-distribution problem in supply-chain management (Abdelmaguid and Dessouky, 2006; Kazarlis et al., 1996; Ravagnani et al., 2005) and optimisation problems in the transport sector (Ahn and Ramakrishna, 2002b; Fan and Machemehl, 2006; Shepherd and Sumalee, 2004; Teklu et al., 2007; Wren and Wren, 1995).

The basic idea of the GA approach is to represent solutions (here a combination of toll charges for different vehicle types) of a problem as a finite length array called a ‘chromosome’ and the objective function value associated with each solution is calculated using a simulation model. The collection of these chromosomes is called the population. A chromosome can be in the form of binary, integer or real number based on the problem. GA uses three genetic operators. Selection, cross-over, and mutation, are those three genetic operators used to search for better solutions in each generation/iteration. The search behavior of GAs is controlled by parameters related to these operators.

Chromosomes with a high fitness level have a higher probability of survival during the selection process. The surviving chromosomes then reproduce and form chromosomes for the next generation through ‘crossover’ and ‘mutation’ processes. The population size used, a number of generations carried out, cross-over and mutation rates are critical for finding better solutions. For example, large populations and generations are quite useful in terms of finding better solutions but consume more computing power. Therefore, for a given problem a suitable population size and number of generations needs to be determined considering the complexity of the problem and solution expected. In this study, sensitivity analysis was conducted to find a combination of population size, a number of generations, cross-over and mutation rates to make sure near-optimal solutions were found. Since GA are a stochastic method, multiple random
seeds were used to minimize the impact of the initial starting population on the optimization results.

However, GA’s do not use much knowledge about the problem to be optimized and do not deal directly with the parameters of the problem. They work with codes which represent the parameters. Therefore, there are some issues that need to be considered when using GA.

I. The first issue in a GA application is how to code the problem under study, i.e. how to represent the problem parameters.

II. GAs operates with a population of possible solutions, not only one possible solution, and the second issue is therefore how to create the initial population of possible solutions.

III. The third issue in a GA application is how to select or devise a suitable set of genetic operators.

IV. Finally, as with other search algorithms, GAs have to know the quality of already found solutions to improve them further. Therefore, there is a need for an interface between the problem environment and the GA itself for the GA to have this knowledge. The design of this interface can be regarded as the fourth issue.

The most critical issue in creating a successful GA involves coding of the chromosomes which must be designed so the GA is not misled.

3.3.5.4 Multi-objective optimization

Multi-objective optimization has been used to solve many complex engineering problems requiring simultaneous consideration of multiple objectives. In a typical multi-objective optimization problem (MOOP) there exists a set of solutions that are superior to the rest of the solutions in the search space considering all objectives but are inferior to each other solutions in terms of at least one of the objectives considered. These solutions are known as Pareto-optimal solutions or non-dominated solutions.

There are classical techniques available in GA to solve multi-objective functions such as objective weighting, distance functions and min-max formulation. However, these
classical methods are not suitable to solve the problem under consideration due to the prior information required to solve the problem. In other words, the decision maker has to know the corresponding weight vector to solve the optimization problem. In addition, once the optimization problem is converted to one single objective, it only produces a single-point solution. However, in real-world problems, the decision maker often needs multiple solutions to choose the most suitable one under given circumstances and thus a single-point solution is not acceptable.

Schaffer in 1984 developed a new algorithm for multi-objective optimization called VEGA (Vector Evaluated Genetic Algorithm) and produced good results. However, it suffered from a bias toward some Pareto-optimal solutions (Srinivas and Deb, 1994). As a result, the Non-dominated Sorting Genetic Algorithm (NSGA) was developed by Srinivas and Deb (1994), eliminating the bias found in VEGA.

3.3.5.4.1 Non-dominated sorting genetic algorithm
NSGA differs from a simple genetic algorithm only in the way the selection operator works. The ranking selection method is used to emphasize good points and a niche method is used to maintain stable sub-populations of good points. Empirical results suggest that NSGA is effective in finding multiple Pareto-optimal solutions and is better than VEGA in that respect. However, there are few drawbacks in NSGA that has been criticized by researchers in the past. Namely;

1. Computational complexity,
2. Non-elitism approach, and
3. Need for specifying a sharing approach

As a solution to the above-mentioned drawbacks in the NSGA, the NSGA-II was developed by Deb et al., (2002). The NSGA-II has been used successfully in solving many multi-objective engineering problems (Bai et al., 2012; Cao et al., 2011; Kuriakose and Shunmugam, 2005; Milosevic and Begovic, 2003; Sarkar and Modak, 2005).

3.3.5.4.2 Pareto-optimal solution and NSGA II
Multi-objective optimization problems, therefore, are defined as ones in which two or more objectives contribute to the overall results. These objectives often affect one
another in complex, non-linear ways (Ombuki et al., 2006). A more precise definition of multi-objective optimization is, where \( n \) objective functions are optimized simultaneously to find a solution. Among the \( n \) objective functions, some functions may be minimized and some functions can be maximized since optimization may occur at both extreme ends (Coello et al., 2007).

Figure 3.7 depicts the solution space for two objectives being optimized which was adapted from (Caramia and Dell’Olmo, 2008). In Figure 3.7, both functions \( F_1(x) \) and \( F_2(x) \) are to be minimised and the solution space is shown with the pareto curve. All the points between \((F_2(a), F_1(b))\) and \((F_2(c), F_1(d))\) define the Pareto front. The shape of the Pareto surface (curve) indicates the nature of the trade-off between different objective functions. The rest of the solutions are known as dominated solutions. Since none of the solutions in the non-dominated set are absolutely better than any other, any one of them is an acceptable solution.

![Figure 0.7: Example of a multi-objective solution space](image)

In general, one way to simplify multi-objective optimization problems is to covert multiple objectives into one single objective by averaging the objectives with a weighting factor as explained above under classical optimization techniques. This converts the multi-objective optimization problem into a single objective optimization problem which is comparatively easier to solve. For example, in this study, it is possible to combine all objectives since all outcomes are measured in dollar terms. However, this
conversion results in a loss of trade-off information between the two conflicting objectives and the assumption of perfect substitutability, where manmade capital can be replaced by natural capital keeping the aggregate total value a constant (Neumayer, 1999; Wu et al., 2009), does not exist. In other words, environmental costs and user costs are not perfectly interchangeable costs even though the dollar amounts match, which is clearly wrong (Neumayer, 1999; Wu et al., 2009). Therefore, a true multi-objective approach is adopted in this study to evaluate the trade-offs between manmade capital (user costs and toll revenue), natural capital (environmental costs) and social capital (social costs). Considering such requirements in the solution, ideally, a Pareto-optimum solution, Non-dominated Sorting Genetic Algorithm II (NSGA II) developed by Deb (2002) was used in this study as the solution algorithm.

3.4 Phase three

3.4.1 Case study networks

Two case study networks were used to demonstrate the application of the model. One is a small hypothetical network and the other is a real-world road network. For both case studies, the road network is defined as a graph $G (N, A)$, where $N$ and $A$ are the sets of nodes and links respectively. $A$ is the set of links without toll charges (highways and other roads) and $\overline{A}$ are the links with toll charges. Let $R$ denote the set of origins and $S$ denotes the set of destinations in an Origin-Destination (OD) matrix. Each O-D pair $r$-$s$ is connected by a set of paths through the network. This set is denoted by $K_{rs}$ where $r \in R$ and $s \in S$. The trip rate between origin $r$ and destination $s$ is defined as $q_{rs}$. Let $K_{rs}$ be the set of paths between OD pair $r$ and $s$, and then $f_{k}^{rs}$ represents the traffic flow on path $k \in K_{rs}$. The traffic flow on link $a \in A \cup \overline{A}$ is denoted by $x_{a}$(veh/hr) and the link travel time is calculated based on the Bureau of Public Roads (BPR) travel time function.

To represent multiple classes of vehicles, four different types of vehicles were considered namely, cars, 2 axle trucks, 4 axle trucks, and 6 axle trucks. Toll charges for all vehicle types were restricted to a minimum of A$0 and a maximum of A$2.55 (equation 8). These boundary values are based on actual values being charged in
Australia (Perera et al., 2016). The operation costs were calculated based on truck operating costs only and values are taken from a previous study (Yang et al., 2016). In other words, car operating costs were not considered in this study, because it is evident from previous studies that irrespective of the route selected by car drivers, there is no significant change in fuel consumption or vehicle operating costs (VOC) for cars (Transport and Infrastructure Council, 2015). However, the value of time for cars varies significantly depending on the number of passengers and trip purpose (Hensher et al., 1990; Hensher and Goodwin, 2004). As a result, it is not representative to calculate a cumulative monetary value for total travel time savings. On the other hand, the time spent on roads has a significant impact on trip choice by users. Therefore, travel times were shown separately rather than being converted into monetary terms. Similarly, the opportunity cost for trucks (if any) was not considered. Vehicle operating time cost (VOTC) for trucks was calculated based on standard market wages paid to drivers and supporting staff.

For both networks considered in this study, it was assumed that the fixed demand condition is typical for a peak one hour and it would continue throughout the years. The following assumptions were also made to calculate the IRR rates under different toll schemes for both case studies. It is assumed that, \( FM_a(C_a) = \alpha I_a(C_a) \), where \( 0 < \alpha \leq 1 \). This implies that the fixed maintenance cost per year is considered as a fixed percentage of the capital cost of the infrastructure. Here, \( \alpha \) is assumed to be 0.01. It was assumed that toll roads operate for 24 hours a day where peak hour volume are equal to 10% of AADT Average Annual Daily Traffic). Capital costs of construction were considered to be A$ 65.8 million/km (or a 4 lane freeway) based on EastLink construction costs of A$ 2.5 billion for a 38km stretch (Perera et al., 2016). The period of operation was considered as 39 years for EastLink (for CityLink its 34 years) before transferring to the client.

### 3.4.2 Hypothetical network

Firstly, a hypothetical road network shown in Figure 3.8 is used to demonstrate the approach. Link numbers shown denote links with traffic flow from west-east direction and the links flowing in the opposite direction are denoted by link numbers with
thousands (e.g. Link 1121 denotes traffic from node 5 to node 10). Additional information about the network is presented in the Appendix. In total there are six toll links considered in this network with a total distance of 3.1 km.

![Hypothetical network structure](image)

**Figure 0.8:** Hypothetical network structure

### 3.4.3 Real-world large road network

#### 3.4.3.1 Background

A real-world road network is also used to demonstrate the application of the model developed. A network including the EastLink freeway in Melbourne, Australia is used. The geographical area extracted from the Google map is shown in Figure 3.9. The schematic diagram of the network is shown in Figure 3.10.
Figure 0.9: Google map with the city of Melbourne and EastLink Road
Figure 0.10: Schematic diagram of the road network around EastLink
EastLink was developed under a PPP and was opened to the public in the year 2008. Beyond this 38 km stretch, this freeway continues as the Eastern freeway towards the north side and as the Frankston Freeway towards the south side. The main objective of this 38 km road was to connect the Eastern, Monash, Frankston and Mornington Peninsula Link freeways in the eastern suburbs of Melbourne. In the cordon considered, only EastLink has toll charges and the other two freeway links within this cordon (Monash and Mornington Peninsula Link) are free of charge for travelers.

EastLink has a simple charging structure for users based on the road sections traveled and is equipped with Electronic Road Pricing (ERP) technology. Therefore, users are equipped with a tag and electronic charging is in place (i.e. no manual tolling booths). Vehicles are categorized into several basic classes with different structures for charging purposes similar to the CityLink (another toll road in Melbourne introduced below).

This large network was created and analyzed using VISUM version 15 (PTV Visum, 2018) a popular commercial software system for transportation planning. Minor local roads are not included in this road network. The network created by VISUM for this study is given in Figure 3.11. Road information was obtained from Open Street Maps (OSM). The speed limits, number of lanes and road layouts were cross-checked using Google street viewer. This network is composed of 7,592 road links, 2,549 nodes, and 335 land zones. Based on real traffic volumes (Average Annual Daily Traffic - AADT) and land zones created, an OD matrix was developed with 306 OD pairs for multi-class traffic.
Figure 0.11: Real-world road network structure
3.4.3.2 Traffic volume data and flow validation

In Victoria, Australia, where Melbourne is located, the administration of road networks is shared by various authorities based on their functionality. Freeways, highways, and collector roads are managed by VicRoads while local roads are managed by respective city councils. AADT volumes were extracted from the publicly available VicRoads website (VicRoads, 2018) for freeways and highways (except the EastLink data). Since EastLink was built as a PPP, traffic volume data are owned and maintained by ConnectEast. These data were obtained from the company for research purposes after a special request. For local roads, AADT’s were obtained from respective city Councils after an official request. These Councils include the local government areas of Greater Dandenong, Monash, Knox, Whitehorse, Maroondah and Frankston.

Rough OD estimates were initially created to cover all vehicle movements in the EastLink area. With many changes and using tools available in VISUM, the final OD matrix was developed for peak hour demand. Based on the additional data (hourly traffic volumes) received from VicRoads through a special request for several major roads in this network, the peak hour volume/AADT ratio was calculated and it varies from 8-11% approximately. Therefore, the peak hour volume/AADT ratio of 10% was used for the entire network. The validity of the OD matrix was checked against the real traffic flow volumes in each link in the modeled network and demonstrated a strong co-relationship with a correlation coefficient of 92%. The modeled network was found to perform well and can be used to predict the major traffic flows under various traffic conditions.

3.5 Phase four

The research goal is, “Development of a Decision-Making Tool for Policy Makers (Government) for determining tolls for freight vehicles minimizing the total cost (economic, social and environmental)”. Since this development requires a multi-stakeholder point of view and different toll strategies proposed may look at a combination of different objectives. In such conditions, we consider what objectives are more important than others, or should everything be treated in an equal manner is debatable. Thus, there is a necessity for investigating the response of multiple
stakeholders to various solutions (alternatives) produced from the model considering economic, environmental and social aspects. As a result, multi-agent multi-criteria analysis (MAMCA) will be used in this study to investigate the multi-stakeholder response to different alternatives produced under various toll schemes. This will enable policy decision makers to clearly understand what schemes are more appropriate to implement under given conditions.

The survey questionnaire is intended to provide the required responses for MAMCA and is described as follows. As mentioned above the proposed freight questionnaire has three parts. Out of which Part A and Part C provide the information required for MAMCA. Part A of the questionnaire collects information regarding freight behavior in an urban context in Melbourne, Australia (which may differ from other urban cities in the world) along with their priorities for different objectives. This information will be used to analyze the basic behavior of truck users in urban context, which will be helpful to propose sustainable freight strategies for the future. Part C of the survey will cover the remaining stakeholder’s response (Government/local authority, residents, toll operators) required for MAMCA.

From the bi-level model explained above various solutions (alternatives) are generated by considering different objectives or as combinations. As mentioned above what weights these different objectives should carry is a common problem when multi-stakeholders are involved and thus MAMCA is used to screen solutions. This provides a clear picture to decision makers to make the best decisions under different conditions.

### 3.5.1 MAMCA Methodology

MAMCA is a methodology to evaluate different policy measures whereby different stakeholders’ opinions are explicitly taken into account. MAMCA has been tested and used to evaluate a number of transport-related strategic decisions in the past (Macharis, 2007), especially in freight transportation. Since the MAMCA methodology has already proven its effectiveness in evaluating complex, sustainable mobility and transport policy decision (Hadavi et al., 2018), MAMCA has been used in this study to solve the toll optimization problem. Figure 3.12 below depicts the 7 steps in MAMCA.
Figure 0.12: Multi-Actor Multi-Criteria Analysis

Source: (Macharis et al., 2009)

 ✓ Step 1: Define alternatives
 ✓ Step 2: Stakeholder Analysis
 ✓ Step 3: Define Criteria and Weights
 ✓ Step 4: Criteria, Indicators, and Measurement Methods
 ✓ Step 5: Overall Analysis and Ranking
 ✓ Step 6: Result
 ✓ Step 7: Implementation
Chapter 4

Truck Cost Model

4.1 Introduction

Externalities produced by trucks are receiving considerable attention at present which sets the direction for this study and thesis. Environmental and Social impacts are known as externalities and usually, these components are negative in nature. These include emissions in terms of CO₂, NOₓ, SO₂ and PM from truck fuel burning and in addition noise and vibration created by truck-fleets conclude environmental costs. Among the most significant and quantifiable elements, accident costs, congestion costs and costs for infrastructure have been considered as social costs. Together all of these are known as externalities which usually have to be borne by the society, who is not directly involved in the operations of transport, or are not the real users. As environmental and social impacts are getting due consideration, it is quite necessary to assess and minimize these externalities in the expedition to sustainable transportation. On the other hand, these externalities are accrued expenses which have to be addressed by actual pricing policies to enable an efficient and sustainable freight transportation system.
Therefore, the objective of this chapter is to identify all cost components for trucks, which includes direct as well as indirect costs and to develop a cost model. This cost model for freight vehicles can be used in mathematical and other models developed in this thesis.

Many institutes and organizations around the world have attempted to quantify different components of truck costs, but so far only limited studies can be found in Europe addressing all components in a comprehensive manner. Therefore, the aim of this chapter is to identify different truck cost components and calculate the most reasonable values for Australia for each component by combining the historical data available. A comprehensive literature review was carried out in order to find out the best values for various sections and most appropriate numbers are produced. However, with evolving technology and developments in infrastructure, these numbers are subject to vary over time. Therefore, in the future, if these numbers are continued to be used, a decent upgrade is essential to fine-tune them with key changes. For example engine performance (efficiency) is being enhanced over time and thus fuel consumption is getting lower for freight vehicles over time. As a result, the cost models need to be updated from time to time to incorporate such changes.

4.2 Classification of truck costs

Truck cost can be broadly divided into two, namely, direct costs and indirect costs. Vehicle operating costs and value of operating time are considered as direct costs whereas environmental and social costs are considered as indirect costs, which are known as externalities as well. Other costs may represent surcharges such as tolls, parking fees, and local taxes. For simplicity purposes, trucks are bundled into a few main types in this study. Figure 4.1 depicts the basic truck cost classifications.
4.3 Vehicle operation cost

Vehicle operation costs (VOC) can be broadly divided into two, based on its type of contribution. Predominantly vehicle operation costs are a function of distance traveled but there is a time-related contribution as well. Figure 4.2 depicts the VOC structure and its sub-elements.
Vehicle operation costs are calculated based on the following equation.

\[ \text{VOC} = C_d + \frac{C_t}{365 \times \theta} \]  

(4.1)

Where;

- \( \text{VOC} \) : vehicle operation cost (A$/km)
- \( C_d \) : cost for distance
- \( C_t \) : cost for time
- \( \theta \) : average working distance per day (km)

Since time-based cost attribution is subjective, past studies have used the average number of kilometers traveled by each truck as the factor to distribute total cost over the variable. By considering past trends, the average working distance for each truck type has been calculated. Therefore, the entire cost calculation is now based on a number of kilometers traveled (no time-related component).

### 4.3.1 Distance based cost

The distance-based cost is a function of the number of parameters such as speed, congestion, acceleration, deceleration, road type and roughness, horizontal and vertical curvature, payload, number of tires, axels, axle combination, and so on. However, some factors are ignored in order to ensure that the calculations are as simple as possible but more relevant factors are considered as appropriate.
Truck cost model

The cost of distance is calculated based on the following equations.

\[ C_d = C_f + C_{ty} + C_m + C_{d1} \]  \hspace{1cm} (4.2)

Where;

- \( C_d \) : Cost for distance
- \( C_f \) : Cost for fuel
- \( C_{ty} \) : Cost for tires
- \( C_m \) : Cost for maintenance
- \( C_{d1} \) : Cost for distance-based depreciation

The equations from 4.3 to 4.7 are used to calculate the sub components of the distance-based vehicle operation costs.

The fuel cost model has two scenarios. One is for stop-start or stop-go conditions which most of the vehicles experience on congested roads where speeds are less than 60km/hr. On the other hand, the second model is for free-flow speed conditions where speeds are comparatively high, on freeways and on highways. Equation 4.3 and equation 4.4 shows the fuel cost calculation formula under stop-start conditions and free-flow conditions respectively.

\[ C_f = p_f (A + \frac{B}{V}) \] \hspace{1cm} Stop-start Model or \hspace{1cm} (4.3)

\[ C_f = p_f (C_0 + C_1 V + C_2 V^2) \] \hspace{1cm} Free-flow condition \hspace{1cm} (4.4)

Where;

- \( A, B, C_0, C_1, C_2 \) : model co-efficient (given in Table 4.1)
- \( P_f \) : fuel price in A$/litre
- \( V \) : average travel speed in km/hr
Table 0.1: Co-efficient for fuel cost calculation

<table>
<thead>
<tr>
<th>Vehicle Type</th>
<th>A</th>
<th>B</th>
<th>C₀</th>
<th>C₁</th>
<th>C₂</th>
<th>p(A$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short</td>
<td>10.487</td>
<td>255.0092</td>
<td>12.3217</td>
<td>-0.0914</td>
<td>0.0009</td>
<td>1.1</td>
</tr>
<tr>
<td>2 Axle Truck</td>
<td>16.0634</td>
<td>147.3128</td>
<td>10.8435</td>
<td>-0.1123</td>
<td>0.0016</td>
<td>1.1</td>
</tr>
<tr>
<td>3 Axle Truck</td>
<td>45.5089</td>
<td>535.1584</td>
<td>32.0378</td>
<td>-0.2949</td>
<td>0.004</td>
<td>1.1</td>
</tr>
<tr>
<td>4 Axle Articulated</td>
<td>63.9608</td>
<td>458.9412</td>
<td>40.1353</td>
<td>-0.3541</td>
<td>0.0053</td>
<td>1.1</td>
</tr>
<tr>
<td>5 Axle Articulated</td>
<td>68.7011</td>
<td>507.3099</td>
<td>42.3944</td>
<td>-0.326</td>
<td>0.0049</td>
<td>1.1</td>
</tr>
<tr>
<td>6 Axle Articulated</td>
<td>75.4028</td>
<td>547.8857</td>
<td>45.8457</td>
<td>-0.3168</td>
<td>0.0049</td>
<td>1.1</td>
</tr>
<tr>
<td>B Double</td>
<td>96.3563</td>
<td>651.9121</td>
<td>56.8966</td>
<td>-0.3128</td>
<td>0.005</td>
<td>1.1</td>
</tr>
<tr>
<td>Double Road Train</td>
<td>112.0411</td>
<td>723.6597</td>
<td>65.1119</td>
<td>-0.3119</td>
<td>0.0051</td>
<td>1.1</td>
</tr>
<tr>
<td>Triple Road Train</td>
<td>145.719</td>
<td>855.7539</td>
<td>82.2758</td>
<td>-0.3084</td>
<td>0.0055</td>
<td>1.1</td>
</tr>
</tbody>
</table>


Equation 4.5 shows the formula used to calculate the tyre costs for multi-class vehicles and Table 4.2 depicts the different tyre types required by freight vehicles and their respective costs.

\[ C_{ty} = \sum_{i} m_i p_{t_i} / d_{l_i} \]  

Where;

\( i \) : tyre type
\( m \): number of type \( i \) tyres
\( p_{t_i} \): price of type \( i \) tyre
\( d_{l_i} \): average mean life of type \( i \) tyre (km)
Table 0.2: Co-efficient for tyre cost calculation

<table>
<thead>
<tr>
<th>Vehicle Type</th>
<th>i</th>
<th>m</th>
<th>P₀ (A$)</th>
<th>dᵢ (km)</th>
<th>Cost (A$)</th>
<th>Total (A$/km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short</td>
<td>1</td>
<td>2</td>
<td>250</td>
<td>50,000</td>
<td>0.0100</td>
<td>0.020</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>2</td>
<td>250</td>
<td>50,000</td>
<td>0.0100</td>
<td></td>
</tr>
<tr>
<td>2 Axle Truck</td>
<td>1</td>
<td>2</td>
<td>250</td>
<td>50,000</td>
<td>0.0100</td>
<td>0.020</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>2</td>
<td>250</td>
<td>50,000</td>
<td>0.0100</td>
<td></td>
</tr>
<tr>
<td>3 Axle Truck</td>
<td>1</td>
<td>4</td>
<td>500</td>
<td>60,000</td>
<td>0.0333</td>
<td>0.052</td>
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<td></td>
<td>2</td>
<td>2</td>
<td>550</td>
<td>60,000</td>
<td>0.0183</td>
<td></td>
</tr>
<tr>
<td>4 Axle Articulated</td>
<td>1</td>
<td>8</td>
<td>700</td>
<td>160,000</td>
<td>0.0350</td>
<td>0.050</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>2</td>
<td>774</td>
<td>100,000</td>
<td>0.0155</td>
<td></td>
</tr>
<tr>
<td>5 Axle Articulated</td>
<td>1</td>
<td>14</td>
<td>700</td>
<td>160,000</td>
<td>0.0613</td>
<td>0.077</td>
</tr>
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<td>2</td>
<td>774</td>
<td>100,000</td>
<td>0.0155</td>
<td></td>
</tr>
<tr>
<td>6 Axle Articulated</td>
<td>1</td>
<td>20</td>
<td>700</td>
<td>160,000</td>
<td>0.0875</td>
<td>0.103</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>2</td>
<td>774</td>
<td>100,000</td>
<td>0.0155</td>
<td></td>
</tr>
<tr>
<td>B Double</td>
<td>1</td>
<td>32</td>
<td>700</td>
<td>160,000</td>
<td>0.1400</td>
<td>0.155</td>
</tr>
<tr>
<td></td>
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<td>2</td>
<td>774</td>
<td>100,000</td>
<td>0.0155</td>
<td></td>
</tr>
<tr>
<td>Double Road Train</td>
<td>1</td>
<td>44</td>
<td>700</td>
<td>160,000</td>
<td>0.1925</td>
<td>0.208</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>2</td>
<td>774</td>
<td>100,000</td>
<td>0.0155</td>
<td></td>
</tr>
<tr>
<td>Triple Road Train</td>
<td>1</td>
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<td>700</td>
<td>160,000</td>
<td>0.2625</td>
<td>0.278</td>
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<td>2</td>
<td>2</td>
<td>774</td>
<td>100,000</td>
<td>0.0155</td>
<td></td>
</tr>
</tbody>
</table>

Source: Freight Metrics, (2016)

Equation 4.6 denotes the formula to calculate the maintenance costs for multi-class vehicles and Table 4.3 depicts the respective co-efficients.

\[
C_m = \sum_i \frac{Cmp_i}{dp_i}
\]  

(4.6)

Where;

\( i \) : type of the component

\( Cmp_i \): cost for fix component \( i \)

\( dp_i \): average mean life of component \( i \) (km)
### Table 0.3: Co-efficient for maintenance costs

<table>
<thead>
<tr>
<th>Vehicle Type</th>
<th>i</th>
<th>Cmp.(A$)</th>
<th>dp, (km)</th>
<th>Total i</th>
<th>Total(A$/km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short</td>
<td>1</td>
<td>350</td>
<td>10,000</td>
<td>0.0350</td>
<td>0.0450</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>200</td>
<td>20,000</td>
<td>0.0100</td>
<td></td>
</tr>
<tr>
<td>2 Axle Truck</td>
<td>1</td>
<td>350</td>
<td>10,000</td>
<td>0.0350</td>
<td>0.0450</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>200</td>
<td>20,000</td>
<td>0.0100</td>
<td></td>
</tr>
<tr>
<td>3 Axle Truck</td>
<td>1</td>
<td>750</td>
<td>18,000</td>
<td>0.0417</td>
<td>0.0667</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>500</td>
<td>20,000</td>
<td>0.0250</td>
<td></td>
</tr>
<tr>
<td>4 Axle Articulated</td>
<td>1</td>
<td>750</td>
<td>18,000</td>
<td>0.0417</td>
<td>0.0667</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>500</td>
<td>20,000</td>
<td>0.0250</td>
<td></td>
</tr>
<tr>
<td>5 Axle Articulated</td>
<td>1</td>
<td>930</td>
<td>18,000</td>
<td>0.0517</td>
<td>0.1352</td>
</tr>
<tr>
<td></td>
<td>2</td>
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<td>0.0835</td>
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<td>6 Axle Articulated</td>
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<td>930</td>
<td>18,000</td>
<td>0.0517</td>
<td>0.1352</td>
</tr>
<tr>
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<td>2</td>
<td>1,670</td>
<td>20,000</td>
<td>0.0835</td>
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</tr>
<tr>
<td>B Double</td>
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<td>930</td>
<td>18,000</td>
<td>0.0517</td>
<td>0.1561</td>
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<tr>
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<td>0.1044</td>
<td></td>
</tr>
<tr>
<td>Double Road Train</td>
<td>1</td>
<td>930</td>
<td>18,000</td>
<td>0.0517</td>
<td>0.2030</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>3,026</td>
<td>20,000</td>
<td>0.1513</td>
<td></td>
</tr>
<tr>
<td>Triple Road Train</td>
<td>1</td>
<td>930</td>
<td>18,000</td>
<td>0.0517</td>
<td>0.2030</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>3,026</td>
<td>20,000</td>
<td>0.1513</td>
<td></td>
</tr>
</tbody>
</table>

*Source: Freight Metrics, (2016)*

Equation 4.7 denotes the formula used to calculate the cost for distance depreciation.

\[
C_{d1} = \alpha (P_0 - P_t)/D_0
\]

(4.7)

Where;

- \(C_{d1}\): Distance related depreciation
- \(P_0\): Cost of a new vehicle
- \(P_t\): Cost of all tyres
- \(D_0\): The average mean life of a vehicle
- \(\alpha\): The percentage of distance depreciation
Depreciation of a truck can be considered as twofold as mentioned above and can be mathematically represented as follows.

\[ \text{Depreciation} = \alpha C_{d1} + (1 - \alpha)C_{d2} \tag{4.8} \]

\( C_{d1} \): Distance related depreciation  \\
\( C_{d2} \): Time related depreciation  \\
\( \alpha \): Proportion of distance depreciation

\( \alpha \) value determines the proportion taken from each component and from the literature it was found to be equal to 0.3 (BC Ministry of Transport, 2012). The cost for distance related depreciation is calculated based on a number of sources and presented in Table 4.4.

**Table 0.4: Co-efficient for distance related depreciation**

<table>
<thead>
<tr>
<th>Vehicle Type</th>
<th>( \alpha )</th>
<th>( P_0 ) (A$)</th>
<th>( P_1 ) (A$)</th>
<th>( D_0 ) (km)</th>
<th>Total(A$/km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short</td>
<td>0.3</td>
<td>37,131</td>
<td>1,000</td>
<td>500,000</td>
<td>0.0217</td>
</tr>
<tr>
<td>2 Axle Truck</td>
<td>0.3</td>
<td>100,956</td>
<td>1,000</td>
<td>500,000</td>
<td>0.0600</td>
</tr>
<tr>
<td>3 Axle Truck</td>
<td>0.3</td>
<td>231,754</td>
<td>3,100</td>
<td>500,000</td>
<td>0.1372</td>
</tr>
<tr>
<td>4 Axle Articulated</td>
<td>0.3</td>
<td>314,904</td>
<td>7,148</td>
<td>600,000</td>
<td>0.1539</td>
</tr>
<tr>
<td>5 Axle Articulated</td>
<td>0.3</td>
<td>351,587</td>
<td>11,348</td>
<td>600,000</td>
<td>0.1701</td>
</tr>
<tr>
<td>6 Axle Articulated</td>
<td>0.3</td>
<td>384,702</td>
<td>15,548</td>
<td>600,000</td>
<td>0.1846</td>
</tr>
<tr>
<td>B Double</td>
<td>0.3</td>
<td>449,987</td>
<td>23,948</td>
<td>600,000</td>
<td>0.2130</td>
</tr>
<tr>
<td>Double Road Train</td>
<td>0.3</td>
<td>569,409</td>
<td>32,348</td>
<td>700,000</td>
<td>0.2302</td>
</tr>
<tr>
<td>Triple Road Train</td>
<td>0.3</td>
<td>728,221</td>
<td>43,548</td>
<td>700,000</td>
<td>0.2934</td>
</tr>
</tbody>
</table>

4.3.2 Time-based costs

The time-based cost is calculated based on the following equations.

\[ C_t = C_i + C_{d2} + C_a + C_r + C_{ins} \]  \hspace{1cm} (4.9)

Where;
- \( C_t \) : Cost for time
- \( C_i \) : Cost for interest
- \( C_{d2} \) : Cost for time depreciation
- \( C_a \) : Cost for administration
- \( C_r \) : Cost for registration
- \( C_{ins} \) : Cost for insurance

Time-based depreciation cost is calculated based on the following equation.

\[ C_{d2} = (1-\alpha)(P_0 - P_t)/n \]  \hspace{1cm} (4.10)

Where;
- \( P_0 \) : Cost of a new vehicle
- \( P_t \) : Cost of all tyres
- \( n \) : Durable years for a vehicle
- \( \alpha \) : The percentage of distance depreciation

Table 4.5 shows the numbers used for time-related depreciation and Table 4.6 depicts the individual costs (all elements) used to calculate the time-based costs for freight vehicles in Australia.
Table 0.5: Figures showing time-related depreciation

<table>
<thead>
<tr>
<th>Type</th>
<th>$P_0$</th>
<th>$P_t$</th>
<th>$\alpha$</th>
<th>$n$</th>
<th>Total (A$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short</td>
<td>37,131</td>
<td>1,000</td>
<td>0.3</td>
<td>10.8</td>
<td>2,342</td>
</tr>
<tr>
<td>2 Axle Truck</td>
<td>100,956</td>
<td>1,000</td>
<td>0.3</td>
<td>11.6</td>
<td>6,032</td>
</tr>
<tr>
<td>3 Axle Truck</td>
<td>231,754</td>
<td>3,100</td>
<td>0.3</td>
<td>17</td>
<td>9,415</td>
</tr>
<tr>
<td>4 Axle Articulated</td>
<td>314,904</td>
<td>7,148</td>
<td>0.3</td>
<td>12.1</td>
<td>17,804</td>
</tr>
<tr>
<td>5 Axle Articulated</td>
<td>351,587</td>
<td>11,348</td>
<td>0.3</td>
<td>12.1</td>
<td>19,683</td>
</tr>
<tr>
<td>6 Axle Articulated</td>
<td>384,702</td>
<td>15,548</td>
<td>0.3</td>
<td>12.1</td>
<td>21,356</td>
</tr>
<tr>
<td>B Double</td>
<td>449,987</td>
<td>23,948</td>
<td>0.3</td>
<td>12.1</td>
<td>24,647</td>
</tr>
<tr>
<td>Double Road Train</td>
<td>569,409</td>
<td>32,348</td>
<td>0.3</td>
<td>12.1</td>
<td>31,070</td>
</tr>
<tr>
<td>Triple Road Train</td>
<td>728,221</td>
<td>43,548</td>
<td>0.3</td>
<td>12.1</td>
<td>39,609</td>
</tr>
</tbody>
</table>


Table 0.6: Time Based Cost Factors

<table>
<thead>
<tr>
<th>Type</th>
<th>$C_i$</th>
<th>$C_a$</th>
<th>$C_{in}$</th>
<th>$C_r$</th>
<th>$C_{d2}$</th>
<th>Total (A$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short</td>
<td>1,207</td>
<td>22,560</td>
<td>2,900</td>
<td>772</td>
<td>2,342</td>
<td>29,780</td>
</tr>
<tr>
<td>2 Axle Truck</td>
<td>2,776</td>
<td>22,560</td>
<td>4,250</td>
<td>896</td>
<td>6,032</td>
<td>35,514</td>
</tr>
<tr>
<td>3 Axle Truck</td>
<td>6,373</td>
<td>22,560</td>
<td>7,600</td>
<td>1,067</td>
<td>9,415</td>
<td>43,715</td>
</tr>
<tr>
<td>4 Axle Articulated</td>
<td>8,660</td>
<td>22,560</td>
<td>17,500</td>
<td>1,937</td>
<td>17,804</td>
<td>58,561</td>
</tr>
<tr>
<td>5 Axle Articulated</td>
<td>9,669</td>
<td>22,560</td>
<td>16,500</td>
<td>1,937</td>
<td>19,683</td>
<td>70,349</td>
</tr>
<tr>
<td>6 Axle Articulated</td>
<td>10,579</td>
<td>22,560</td>
<td>17,500</td>
<td>1,937</td>
<td>21,356</td>
<td>73,932</td>
</tr>
<tr>
<td>B Double</td>
<td>12,375</td>
<td>22,560</td>
<td>18,810</td>
<td>9,878</td>
<td>24,647</td>
<td>88,270</td>
</tr>
<tr>
<td>Double Road Train</td>
<td>15,659</td>
<td>22,560</td>
<td>21,660</td>
<td>10,866</td>
<td>31,070</td>
<td>101,814</td>
</tr>
<tr>
<td>Triple Road Train</td>
<td>20,026</td>
<td>22,560</td>
<td>21,660</td>
<td>10,866</td>
<td>39,609</td>
<td>114,721</td>
</tr>
</tbody>
</table>


Finally, the vehicle operating cost functions are developed as follows for two different traffic (speed) conditions and the coefficients are given in Table 4.7 below.

\[
VOC_{FF} = a_2 x^2 + a_1 x + a_0 \tag{4.11}
\]

\[
VOC_{SG} = b_0 + \frac{b_1}{x} \tag{4.12}
\]

Where; $x$ is given by speed.
Table 0.7: Vehicle operating costs co-efficients

<table>
<thead>
<tr>
<th>Vehicle Type</th>
<th>Free-Flow Condition (60-100 kmph)</th>
<th>Stop-go condition (60-10 kmph)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$a_2$</td>
<td>$a_1$</td>
</tr>
<tr>
<td>Short</td>
<td>9.9E-06</td>
<td>-0.0015</td>
</tr>
<tr>
<td>2 Axle Truck</td>
<td>1.76E-05</td>
<td>-0.0012</td>
</tr>
<tr>
<td>3 Axle Truck</td>
<td>4.4E-05</td>
<td>-0.0032</td>
</tr>
<tr>
<td>4 Axle Articulated</td>
<td>5.83E-05</td>
<td>-0.0038</td>
</tr>
<tr>
<td>5 Axle Articulated</td>
<td>5.39E-05</td>
<td>-0.0035</td>
</tr>
<tr>
<td>6 Axle Articulated</td>
<td>5.39E-05</td>
<td>-0.0034</td>
</tr>
<tr>
<td>B Double</td>
<td>5.5E-05</td>
<td>-0.0034</td>
</tr>
<tr>
<td>Double Road Train</td>
<td>5.61E-05</td>
<td>-0.0034</td>
</tr>
<tr>
<td>Triple Road Train</td>
<td>6.05E-05</td>
<td>-0.0033</td>
</tr>
</tbody>
</table>

4.4 Value of operating time

This is purely from the cost contribution made by the truck operator and his assistant (if available) over the operation time of the truck, which could be considered under vehicle operation cost as well. In other words, the value of operating time (VOT) needs to be added to the VOC to arrive at full vehicle operation cost value. In this study, this figure was discussed separately since it may sometimes require separating this number from the main figure. However, it is important to note that this is different from willingness to pay by each user for each minute of travel time (or delay), which is heavily dependent on other parameters such as load, load type (freight type), receivers’ perception, time of the day, and so on.

Based on the literature the following simple equation can be used to measure the VOT.

\[
VOT = \frac{(C_{wa} + C_{at})}{H_w}
\]  

(4.13)

Where;

$VOT$ : Value of Operating Time (A$/min)$
Truck cost model

\[ C_{wa} \] : Cost for Driver's min wage per week (A$/week)

\[ C_{al} \] : Cost for Allowance (Meal+ Overnight+ Aid)

\[ H_w \] : Min working hours per week (h)

After considering a number of basic publications such as ‘Freight Calculator Australia’ and web publications the numbers presented in Table 4.8 were selected as reasonable.

**Table 0.8: Value of operating time**

<table>
<thead>
<tr>
<th>Type</th>
<th>Hourly Wage (A$/hr)</th>
<th>Average Wage Rate (A$/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short</td>
<td>28.16</td>
<td>0.469</td>
</tr>
<tr>
<td>2 Axle Truck</td>
<td>28.16</td>
<td>0.469</td>
</tr>
<tr>
<td>3 Axle Truck</td>
<td>28.68</td>
<td>0.478</td>
</tr>
<tr>
<td>4 Axle Articulated</td>
<td>29.37</td>
<td>0.490</td>
</tr>
<tr>
<td>5 Axle Articulated</td>
<td>29.80</td>
<td>0.497</td>
</tr>
<tr>
<td>6 Axle Articulated</td>
<td>29.80</td>
<td>0.497</td>
</tr>
<tr>
<td>B Double</td>
<td>30.66</td>
<td>0.511</td>
</tr>
<tr>
<td>Double Road Train</td>
<td>30.66</td>
<td>0.511</td>
</tr>
<tr>
<td>Triple Road Train</td>
<td>31.18</td>
<td>0.520</td>
</tr>
</tbody>
</table>

*Source: Freight Metrics, (2016)*

### 4.5 Social costs

![Social Costs](chart)

**Figure 0.3: Social costs classification flow chart**
4.5.1 Accident costs

There is no straightforward ideal methodology developed so far to evaluate the accident costs that each vehicle user has to bear with when they are on roads. Different methodologies have been introduced in the literature to measure the accident risk which is different from accident cost as a social costs parameter. However, the similar methodology can be used to quantify the accident cost, which ultimately has to be distributed among road users, or respective road users, and thus this study has focused on the development of such rates for Australia based on available data. From the literature, the following costs were identified as the components contributing to accident costs:

- Expected costs (of death and injury) due to an accident for the person exposed to risk,
- Expected costs for the relatives and friends of the person exposed to risk,
- Accident costs for the rest of the society (output loss, material costs, police and medical costs).

The first two cost elements are evaluated using the concept of willingness to pay for safety. The key indicator upon which the evaluation is carried out is the value of a statistical life (VSL). Usually, the assumption is made that the users internalize in their decisions the risk they expose themselves and their family too, valued as their willingness-to-pay for safety.

Even though there are many sophisticated ways that are outlined in literature, a simple yet reasonably accurate method was initially used here to calculate accident costs for Australia based on available data.

Table 0.9: Number of crashes on different roads per 100 million vkm

<table>
<thead>
<tr>
<th>Road Type</th>
<th>Casualty</th>
<th>Serious Casualty</th>
<th>Fatal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freeway</td>
<td>4.38</td>
<td>1.61</td>
<td>0.12</td>
</tr>
<tr>
<td>Highway</td>
<td>17.57</td>
<td>6.52</td>
<td>0.44</td>
</tr>
</tbody>
</table>

Source: VicRoads
Table 0.10: Updated average crash costs using the human capital approach, 2013

<table>
<thead>
<tr>
<th>Crash severity</th>
<th>Fatal</th>
<th>Serious injury</th>
<th>Slight injury</th>
<th>PDO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value (A$ 2013)</td>
<td>2,463,432</td>
<td>629,484</td>
<td>22,992</td>
<td>9,257</td>
</tr>
</tbody>
</table>

Source: Adapted from BTE (2000), available at NGTSM report

However, there is no vehicle specific values for this calculation and the same numbers will be used for all types of vehicles indicated as follows.

Table 0.11: Accident cost by road type and vehicle type (A$/km)

<table>
<thead>
<tr>
<th>Vehicle Type</th>
<th>Freeway</th>
<th>C_{ac}</th>
<th>Highway</th>
</tr>
</thead>
<tbody>
<tr>
<td>For all vehicle types</td>
<td>0.014098</td>
<td>0.055921</td>
<td></td>
</tr>
</tbody>
</table>

Therefore, a more detailed version of the calculation was carried out based on the available data in Australia in order to determine more relevant figures for each vehicle type and road types. However, the output loss (to other users of the facility in a crash situation) as a result of the crash is not yet quantified since it’s a very vague to quantify. The flowchart shown in Figure 4.4 below depicts the process of the new crash cost calculation implemented.
Figure 0.4: New accident cost calculation process flowchart

Table 0.12: Revised accident costs by road type and vehicle type (A$/km)

<table>
<thead>
<tr>
<th>Type</th>
<th>Freeway</th>
<th>Highway</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>Car</td>
<td>0.0088</td>
<td>0.0703</td>
<td>0.0703</td>
</tr>
<tr>
<td>Short</td>
<td>0.0064</td>
<td>0.0782</td>
<td>0.0412</td>
</tr>
<tr>
<td>2 and 3 Axle Trucks</td>
<td>0.0076</td>
<td>0.0364</td>
<td>0.0260</td>
</tr>
<tr>
<td>All Articulated Trucks</td>
<td>0.0121</td>
<td>0.0800</td>
<td>0.0212</td>
</tr>
</tbody>
</table>

Since crash costs (Accident costs) are calculated as an exposure function considering number of vehicles in each class on different road type, the accident cost can be mathematically constructed as;

\[
AC_a^m = f(x_a^m) \quad \forall \quad a \in A \cup \overline{A}, \quad m \in M \tag{4.14}
\]

Therefore, the total crash cost can be calculated as:

\[
\sum_a \sum_m AC_a^m x_a^m d_a \quad \forall \quad a \in A, m \in M \tag{4.15}
\]

Where,

\[x_a^m\] : Traffic flow on the link \( a \) w.r.t vehicle type, \( a \in A \cup \overline{A}, m \in M \) (veh/hr)

\[d_a\] : The distance of link \( a \), \( \forall \quad a \in A \cup \overline{A} \) (meters)

\[AC_a^m\] : Accident cost vector with road type for a given link \( a \), \( a \in A \cup \overline{A}, m \in M \) (A$/vkm)

4.5.2 Congestion cost

The concept of congestion externalities is easy to understand but difficult to quantify. As a result, no such calculation was found in Australia which can be ready to use.

As stated in the, ‘Handbook on External Costs of Transportations’ congestion cost can be illustrated as; “A user of a road network effects, by his/her decision to use the
network for driving from A to B, the utility of all other users who want to use the same network capacity. The utility loss, aggregated over all those other users, is the negative external effect of the respective user’s decision to go from A to B. As utility itself cannot sensibly be added up, the utility is first translated to monetary terms before aggregation, i.e. the willingness to pay for avoiding the utility loss. Thus, the external effect is measured in terms of a monetary amount per trip.”

Since no valid numbers are available in Australia, numbers developed in Europe have been used in this study after a rate and time conversion. The conversion was done based on the GDP per capita ratio in Europe (2010) and in Australia (2016).

Congestion was measured based on the v/c ratio of each road type and only three road types were considered in this study for simplicity. However, vehicles are only classified into rigid trucks and articulated trucks in the original study and thus numbers are repetitive for few types of vehicles considered here.

Since congestion costs (A$/km) are a function of the v/c ratio and class-specific vehicle volumes, $x^m_a$, the congestion cost can be mathematically formulated as:

$$CC^m_a = f(x^m_a, x_a/C_a) \quad \forall \; a \in A \cup \bar{A}, m \in M \quad (4.16)$$

Therefore, the total congestion cost can be calculated as:

$$\sum_a \sum_m CC^m_a x^m_a d_a \quad \forall \; a \in A, m \in M \quad (4.17)$$

The relevant cost figures are extracted from the literature and presented in Tables 4.13, 4.14 and 4.15 below.
**Table 0.13:** Congestion cost under free-flow condition on different road types

<table>
<thead>
<tr>
<th>Type</th>
<th>( C_{\text{cong}}(A$/vkm) )</th>
<th>Free flow (v/c &lt; 0.25)</th>
<th>Motorway</th>
<th>Main roads</th>
<th>Other roads</th>
</tr>
</thead>
<tbody>
<tr>
<td>Car</td>
<td>0.000</td>
<td>0.016</td>
<td>0.043</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Short</td>
<td>0.000</td>
<td>0.016</td>
<td>0.043</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 &amp; 3 Axle Trucks</td>
<td>0.000</td>
<td>0.031</td>
<td>0.081</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4, 5 &amp; 6 Axle Articulated</td>
<td>0.000</td>
<td>0.047</td>
<td>0.125</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B Double</td>
<td>0.000</td>
<td>0.047</td>
<td>0.125</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Double &amp; Triple Road Train</td>
<td>0.000</td>
<td>0.047</td>
<td>0.125</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Source: Korzhenevych and Dehnen, (2014)*

**Table 0.14:** Congestion cost under the near capacity condition on different road types

<table>
<thead>
<tr>
<th>Type</th>
<th>( C_{\text{cong}}(A$/vkm) )</th>
<th>Near capacity (v/c &lt; 1)</th>
<th>Motorway</th>
<th>Main roads</th>
<th>Other roads</th>
</tr>
</thead>
<tbody>
<tr>
<td>Car</td>
<td>0.465</td>
<td>2.450</td>
<td>2.766</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Short</td>
<td>0.465</td>
<td>2.450</td>
<td>2.766</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 &amp; 3 Axle Trucks</td>
<td>0.883</td>
<td>4.656</td>
<td>5.254</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4, 5 &amp; 6 Axle Articulated</td>
<td>1.346</td>
<td>7.106</td>
<td>8.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B Double</td>
<td>1.346</td>
<td>7.106</td>
<td>8.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Double &amp; Triple Road Train</td>
<td>1.346</td>
<td>7.106</td>
<td>8.020</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Source: (Korzhenevych and Dehnen, 2014)*

**Table 0.15:** Congestion cost under over capacity condition on different road types

<table>
<thead>
<tr>
<th>Type</th>
<th>( C_{\text{cong}}(A$/vkm) )</th>
<th>Over capacity (v/c &gt; 1)</th>
<th>Motorway</th>
<th>Main roads</th>
<th>Other roads</th>
</tr>
</thead>
<tbody>
<tr>
<td>Car</td>
<td>1.066</td>
<td>3.144</td>
<td>4.207</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Short</td>
<td>1.066</td>
<td>3.144</td>
<td>4.207</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 &amp; 3 Axle Trucks</td>
<td>2.027</td>
<td>5.972</td>
<td>7.992</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4, 5 &amp; 6 Axle Articulated</td>
<td>3.093</td>
<td>9.114</td>
<td>12.199</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B Double</td>
<td>3.093</td>
<td>9.114</td>
<td>12.199</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Double &amp; Triple Road Train</td>
<td>3.093</td>
<td>9.114</td>
<td>12.199</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Source: Korzhenevych and Dehnen, (2014)*
4.5.3 Infrastructure costs

Infrastructure costs (IC) can be broadly categorized into three elements. Namely, fixed costs, variable costs, and profits from infrastructure development (e.g. PPP Projects). Fixed costs (capital investment) can be shown as a cost per kilometer based on the number of lanes of the road which affect the capacity. Variable costs can be subdivided into two based on its nature of expenditure. First as non-usage based fixed annual costs and secondly as a usage-based (variable) element. Finally, profits are determined based on market rates and the terms and conditions of the agreement made with the road authority. Since only some road links are built under PPPs and other links are mainly funded through government budgets using the taxes of resident’s, capital cost investment is set apart from the infrastructure costs in this study. As a result, IC are more focused on routine costs or costs that can be charged based on usage. Therefore, the IC considered here are limited to the maintenance and administrative costs of the road facility.

Maintenance costs are calculated based on the damage caused by each vehicle type when traveling on various types of roads. In other words, the maintenance costs for each facility have been distributed among different vehicles based on their usage or damage caused to the pavement. ESALs are used to measure the damage caused by each vehicle type similar to the highway design and the cost is distributed over a number of kilometers traveled on each facility type.

Therefore, maintenance and administration costs (A$/km/veh. type) can be considered simply as a function of a number of vehicles on that link for a unit of time (per year).

\[ IC^m_a = f(M^m_a, x^m_a) \quad \forall \ a \in A \cup \tilde{A}, \ m \in M \]  \hspace{1cm} (4.18)

\( M^m_a \) is taken from literature and presented in Table 4.16. Therefore, the infrastructure costs can be calculated as:

\[ \sum_a \sum_m IC^m_a \cdot x^m_a \cdot d_a \quad \forall \ a \in A, \ m \in M \]  \hspace{1cm} (4.19)
Table 0.16: Infrastructure costs

<table>
<thead>
<tr>
<th>Type</th>
<th>C_{inf}(A$/ vkm)</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Motorway</td>
<td>Main roads</td>
<td>Other roads</td>
</tr>
<tr>
<td>Car</td>
<td>0.003</td>
<td>0.005</td>
<td>0.014</td>
</tr>
<tr>
<td>Short</td>
<td>0.005</td>
<td>0.009</td>
<td>0.021</td>
</tr>
<tr>
<td>2 Axle Truck</td>
<td>0.028</td>
<td>0.047</td>
<td>0.373</td>
</tr>
<tr>
<td>3 Axle Truck</td>
<td>0.038</td>
<td>0.062</td>
<td>0.501</td>
</tr>
<tr>
<td>4 Axle Articulated</td>
<td>0.049</td>
<td>0.080</td>
<td>0.636</td>
</tr>
<tr>
<td>5 Axle Articulated</td>
<td>0.057</td>
<td>0.097</td>
<td>0.773</td>
</tr>
<tr>
<td>6 Axle Articulated</td>
<td>0.035</td>
<td>0.057</td>
<td>0.463</td>
</tr>
<tr>
<td>B Double</td>
<td>0.055</td>
<td>0.092</td>
<td>0.733</td>
</tr>
<tr>
<td>Double Road Train</td>
<td>0.075</td>
<td>0.125</td>
<td>1.001</td>
</tr>
<tr>
<td>Triple Road Train</td>
<td>0.137</td>
<td>0.227</td>
<td>1.821</td>
</tr>
</tbody>
</table>

Source: Korzhenevych and Dehnen, (2014)

To maintain the accuracy as far as possible, the numbers were checked with available Australian data with a bottom-up approach. With the number of vehicle kilometres travelled (VKT) by each vehicle type given in the PAYGO model (NTC Australia, 2014) with respect to road type (only two road types are considered) multiplied with respective values in the above Table gave an answer as the total cost of A$ 3,200 million which is close to value assigned by the PAYGO model for heavy vehicles in year 2016. Therefore, these numbers seem to be fairly representative of Australian conditions and maybe fine-tuned further as more data becomes available.
4.6 Environmental costs

Environmental costs mainly consist of two components, namely, emission costs and noise costs. Figure 4.5 depicts the environmental costs structure.

![Environmental Costs Diagram](image)

**Figure 0.5**: Environmental cost components

Emissions are a direct output from fuel combustion and noise is generated from vehicle operations. The quantification of explicit impacts on human health, environment, and economic activity has been considered in evaluating such costs. The amount of pollutants, dispersion, exposure (to humans), and impact on health or ecology and finally damage caused are the key sectors considered in the cost evaluation process. Environmental costs can be calculated as shown in equation 4.20.

\[
EC = \sum_i C_e i \times C_f \times E_i + C_{no} \tag{4.20}
\]

Where;

- \(EC\) - environmental costs
- \(i\) - emission type
- \(C_e\) - cost of emissions
- \(C_f\) - fuel consumption per km (in litres, where \(p=1\))
- \(E_i\) - weight of emissions
- \(C_{no}\) - cost of noise
4.6.1 Emission costs

Emissions from multiple classes of vehicles under various conditions and respective costs (based on negative impacts) to the humans and the environment have been considered in this study. The main source used in this study was the, ‘Road parameter values’ published by Transport and Infrastructure Council which has extensively considered different models developed in Australia so far to arrive at the most accurate numbers. In order to estimate fuel consumption for multi-class vehicles at various travel speeds, the Road Parameter Values study considered previous models developed by Cox and Arup (1996) and Austroads (2004). These models were solely produced for the purpose of evaluation of transport projects and are quite compatible with the latest study results such as the, ‘Carbon Dioxide Emissions Intensity for New Australian Light Vehicles’ (NTC Australia, 2017).

The average fuel consumption for each vehicle type, under a given speed, has been used to estimate the emissions generated using conversion factors presented by the Transport and Infrastructure Council, (2015). The numbers have been calculated based on COPERT for Australia and models developed by BITRE (Bureau of Infrastructure, Transport, and Regional Economics). These estimates have also been compared with results reported in studies carried out by the Department of the Environment (Smit, 2014).

The most significant and harmful emission types were considered in this study, including carbon dioxide (CO₂), nitrogen oxide (NOₓ), sulfur oxide (SOₓ) and particulate matter (PM2.5). In order to calculate the damage costs of each pollutant type, external cost models published by the European groups (Korzhenevych et al., 2014; Preiss and Klotz, 2007; Rouhani and Niemeier, 2014; van Essen et al., 2011) were used. In this model, the health impacts caused by toxic pollutants from road transportation were quantified in monetary terms. The impact of GHG’s was considered separately in terms of damage caused to building and materials, crop losses, biodiversity and ecosystems. The costs were converted to Australian Dollars (A$) using the GDP ratio (Korzhenevych et al., 2014) and shown in Table 4.17 below.
Table 0.17: Cost of emissions (Ce)

<table>
<thead>
<tr>
<th>SO₂(A$/g)</th>
<th>PM₂.₅(A$/g)</th>
<th>NOₓ(A$/g)</th>
<th>CO₂(A$/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.018</td>
<td>0.469</td>
<td>0.0185</td>
<td>0.156</td>
</tr>
</tbody>
</table>

*Source: Korzhenevych and Dehnen, (2014)*

Considering the above facts, the emission costs can be written as a function of:

\[
E^m_a = f(e^m_i, e^c_i, v_a, f^m(v), x^m_a) \tag{4.21}
\]

Where,

- \( e^m_i \): Different emission types \((i)\) given by weight \((g\text{ or }kg)\) per vehicle type per litre of fuel consumed \((g\text{ or }kg/\text{one litre of fuel})\)
- \( e^c_i \): Cost by weight \((g\text{ or }kg)\) for different emission type \((i)\) \((A$/g\text{ or }kg)\)
- \( v_a \): Average speed on the link \(a\) \((km/hr)\)
- \( f^m(v) \): Fuel consumption per kilometer travelled by each vehicle class under given speed \((litres)\)

\(i = 1\) for CO₂, \(i = 2\) for PM₂.₅, \(i = 3\), for NOₓ and \(i = 4\) for SOₓ

The emissions model above utilizes the average speed (average speed of the link as the speed of all vehicles traversing on that link) to calculate the fuel consumption for multi-class vehicles. As explained in Chapter 8, more sophisticated speed models such as running speed models, instantaneous or elemental models have not been used due to their complexity. However, the stop-go and free flow running conditions have been considered in this study, which is more important to generate accurate results in a network study.

Since the age of a vehicle (based on year of manufacture) is a major contributing factor for emissions, the age of a vehicle was considered as a variable in this study. The average age of a vehicle type (for multi-class) was considered based on Motor Vehicle Census data (ABS, 2018). Accordingly, all light commercial vehicles were assumed to be manufactured between 2004 and 2005 and all heavy vehicles were assumed to be manufactured between 2003-2008. And all cars were assumed as manufactured after
2008. Table 4.18 depicts the pollution production by each vehicle class with respect to their age.

<table>
<thead>
<tr>
<th>Vehicle Type &amp; Year of Manufacture</th>
<th>SO₂ (g/l)</th>
<th>PM₁₀ (g/l)</th>
<th>NOₓ (g/l)</th>
<th>CO₂ (kg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Car</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Post-08</td>
<td>0.172</td>
<td>0.012</td>
<td>0.77</td>
<td>2.282</td>
</tr>
<tr>
<td>06~08</td>
<td>0.172</td>
<td>0.018</td>
<td>1.14</td>
<td>2.282</td>
</tr>
<tr>
<td>04~05</td>
<td>0.172</td>
<td>0.025</td>
<td>1.98</td>
<td>2.282</td>
</tr>
<tr>
<td>98~03</td>
<td>0.172</td>
<td>0.048</td>
<td>6.42</td>
<td>2.282</td>
</tr>
<tr>
<td>86~97</td>
<td>0.172</td>
<td>0.131</td>
<td>15.33</td>
<td>2.282</td>
</tr>
<tr>
<td>76~85</td>
<td>0.172</td>
<td>0.175</td>
<td>25.12</td>
<td>2.282</td>
</tr>
<tr>
<td>pre~76</td>
<td>0.172</td>
<td>0.258</td>
<td>26.10</td>
<td>2.282</td>
</tr>
<tr>
<td><strong>LCV</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Post-08</td>
<td>0.017</td>
<td>0.261</td>
<td>3.28</td>
<td>2.6712</td>
</tr>
<tr>
<td>06~08</td>
<td>0.017</td>
<td>0.498</td>
<td>5.88</td>
<td>2.6712</td>
</tr>
<tr>
<td>04~05</td>
<td>0.017</td>
<td>0.549</td>
<td>8.17</td>
<td>2.6712</td>
</tr>
<tr>
<td>98~03</td>
<td>0.017</td>
<td>0.836</td>
<td>16.96</td>
<td>2.6712</td>
</tr>
<tr>
<td>86~97</td>
<td>0.017</td>
<td>1.05</td>
<td>22.32</td>
<td>2.6712</td>
</tr>
<tr>
<td>76~85</td>
<td>0.017</td>
<td>1.666</td>
<td>24.32</td>
<td>2.6712</td>
</tr>
<tr>
<td>pre~76</td>
<td>0.017</td>
<td>3.458</td>
<td>27.14</td>
<td>2.6712</td>
</tr>
<tr>
<td><strong>HCV</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Post-08</td>
<td>0.017</td>
<td>0.107</td>
<td>9.41</td>
<td>2.6712</td>
</tr>
<tr>
<td>03~08</td>
<td>0.017</td>
<td>0.294</td>
<td>16.7</td>
<td>2.6712</td>
</tr>
<tr>
<td>96~02</td>
<td>0.017</td>
<td>0.898</td>
<td>22.19</td>
<td>2.6712</td>
</tr>
<tr>
<td>pre~96</td>
<td>0.017</td>
<td>1.626</td>
<td>27.71</td>
<td>2.6712</td>
</tr>
</tbody>
</table>


*(Smit, 2014)*

Since the speed of a vehicle was classified into two different flow conditions, free-flow conditions and stop-go conditions, two equations were used to estimate the emissions costs:
Truck cost model

\[ EC_{FF} = a_2 v^2 + a_1 v + a_0 \]  
\[ EC_{SG} = c_0 + c_1 / v \]

where

\( EC_{FF} \): Emission cost for given vehicle type under free-flow conditions (A$/km)

\( EC_{SG} \): Emission cost for given vehicle type under stop-go conditions (A$/km)

\( a_2, a_1, a_0, c_0, c_1 \): Coefficients, values of which for multi-class vehicles under two flow conditions are given in Table 4.19 below.

Therefore, the total emissions cost can be calculated as:

\[ \sum_{a} \sum_{m} \left[ (a_2 v_a^2 + a_1 v_a + a_0) + \left( c_0 + \frac{c_1}{v_a} \right) \beta \right] x_a^m d_a \quad \forall \, a \in A \cup \bar{A}, \, m \in M \]  
\[ (4.24) \]

\[ \text{if } 100 \geq v_a \geq 60, \, \gamma = 1, \, 0 \, \text{otherwise} \]  
\[ (4.25) \]

\[ \text{if } 60 > v_a \geq 10, \, \beta = 1, \, 0 \, \text{otherwise} \]  
\[ (4.26) \]

where

\( d_a \): The distance of link \( a, \forall \, a \in A \cup \bar{A} \) (meters)

Equation (4.24) represents the total emissions cost with non-negativity vehicle speed constraint (not given here). Equations (4.25) and (4.26) denote the applicability of \( \gamma \) and \( \beta \) based on respective average link speed.
Table 0.19: Emission cost co-efficient

<table>
<thead>
<tr>
<th>Vehicle Type</th>
<th>Free-Flow Conditions (60-100 kmph)</th>
<th>Stop-go conditions (60-10 kmph)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>a₂</td>
<td>a₁</td>
</tr>
<tr>
<td>Car</td>
<td>3.03E-06</td>
<td>-0.00029</td>
</tr>
<tr>
<td>Short Vehicle</td>
<td>7.43E-06</td>
<td>-0.00075</td>
</tr>
<tr>
<td>2 Axle Truck</td>
<td>1.32E-05</td>
<td>-0.00093</td>
</tr>
<tr>
<td>3 Axle Truck</td>
<td>3.45E-05</td>
<td>-0.00255</td>
</tr>
<tr>
<td>4 Axle Articulated</td>
<td>4.57E-05</td>
<td>-0.00310</td>
</tr>
<tr>
<td>5 Axle Articulated</td>
<td>4.23E-05</td>
<td>-0.00280</td>
</tr>
<tr>
<td>6 Axle Articulated</td>
<td>4.23E-05</td>
<td>-0.00273</td>
</tr>
<tr>
<td>B Double</td>
<td>4.32E-05</td>
<td>-0.00270</td>
</tr>
<tr>
<td>Double Road</td>
<td>4.40E-05</td>
<td>-0.00270</td>
</tr>
<tr>
<td>Triple Road Train</td>
<td>4.75E-05</td>
<td>-0.00270</td>
</tr>
</tbody>
</table>

It should be noted that a recent study on CO₂ emissions by LCV in Australia has relieved that numbers used in Europe studies are approximately 36% below the Australian average (NTC Australia, 2017). Therefore, these numbers are very prudent but need to be raised by a significant percentage in the near future once detail information is available.

4.6.2 Noise costs

Noise refers to unwanted sound and vibration. Noise pollution in road transportation is mainly caused by the sound of the vehicle engine and the sound of rolling (Demir et al., 2015). In addition, vibration, horns, vehicle theft alarms, and braking are also contributing factors for road noise or pollution. Heavy vehicles are known to produce vibration and low-frequency noise (VTPI, 2018). According to Brown and Lam (1994), approximately 1/3 of houses experience significant traffic noise.

Cost of noise is a function of various parameters. Two major impacts are usually considered when assessing noise impacts:

1. Annoyance, reflecting the disturbance which individuals experience when exposed to (traffic) noise. This may hinder the communication and enjoyment of leisure activities.
2. Health impacts, related to the long-term exposure to noise, mainly stress-related health effects like hypertension and myocardial infarction.

Information required for the calculation of noise pollution includes vehicle type, engine type, payload, traffic condition, speed, stops, road gradient, road surface type, and condition and impact duration are one set of parameters and exposure to population (density) is another set of parameters such as distance from population densities to noise source, barriers, and time of day (VTPI, 2018).

Therefore, the noise costs can be mathematically denoted as:

\[
N_{Ca}^m = f(x_a^m, x_a/C_a, L_t) \quad \forall \quad a \in A \cup \bar{A}, m \in M \tag{4.27}
\]

Where,

\(L_t\) – time of day, \(t = 1\) for day and \(t = 2\) for night

The total noise costs can be calculated as:

\[
\sum_a \sum_m N_{Ca}^m x_a^m d_a \quad \forall \quad a \in A, m \in M \tag{4.28}
\]

Equation (4.27) denotes the noise cost as a function of vehicle type, number of vehicles, v/c ratio and time of the day. Equation (4.28) represents the total noise cost calculated for given conditions. The coefficients required to calculate noise costs are given in Table 4.20.

Many studies in the past have attempt to develop noise models (Demir et al., 2015; Kephalopoulos et al., 2011; WSEAS International Conference on Applied and Theoretical Mechanics et al., 2009) but no attempt was made to convert it into monitory terms which can be used to quantify the effect. Therefore, this study has relied on the following information mainly extract from the External Costs of Transport in Europe, 2011 (CE Delft, INFRAS, Fraunhofer ISI, 2011) report. For simplicity purposes, surrounding conditions are considered as urban only.
**Table 0.20:** Noise costs in urban areas under the different time of day and traffic conditions

<table>
<thead>
<tr>
<th>Vehicle Type</th>
<th>C_{no}(urban)</th>
<th>Traffic Condition-Day</th>
<th>Traffic Condition-Night</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Dense</td>
<td>Thin</td>
</tr>
<tr>
<td>Car</td>
<td>0.0132</td>
<td>0.0321</td>
<td>0.02415</td>
</tr>
<tr>
<td>Short</td>
<td>0.066</td>
<td>0.1605</td>
<td>0.12045</td>
</tr>
<tr>
<td>2 Axle Truck</td>
<td>0.066</td>
<td>0.1605</td>
<td>0.12045</td>
</tr>
<tr>
<td>3 Axle Truck</td>
<td>0.066</td>
<td>0.1605</td>
<td>0.12045</td>
</tr>
<tr>
<td>4 Axle Articulated</td>
<td>0.1215</td>
<td>0.2949</td>
<td>0.2217</td>
</tr>
<tr>
<td>5 Axle Articulated</td>
<td>0.1215</td>
<td>0.2949</td>
<td>0.2217</td>
</tr>
<tr>
<td>6 Axle Articulated</td>
<td>0.1215</td>
<td>0.2949</td>
<td>0.2217</td>
</tr>
<tr>
<td>B Double</td>
<td>0.1215</td>
<td>0.2949</td>
<td>0.2217</td>
</tr>
<tr>
<td>Double Road Train</td>
<td>0.1215</td>
<td>0.2949</td>
<td>0.2217</td>
</tr>
<tr>
<td>Triple Road Train</td>
<td>0.1215</td>
<td>0.2949</td>
<td>0.2217</td>
</tr>
</tbody>
</table>

*Source: External Costs of Transport in Europe, 2011*
Chapter 5

Analysis of Toll Charges for Freight Vehicles in Melbourne

5.1 Introduction

There has been an increasing worldwide tendency towards the introduction of commercially and privately funded roads for building and operating modern road systems (Broaddus and Gertz, 2008; de Palma and Lindsey, 2000; Odeck and Bråthen, 2002; Yang et al., 2002). Many Australian freeways are developed on Public-Private Partnership (PPP) or Build-Own-Operate-Transfer (BOOT) scheme and toll charges provide the revenue for the investment. CityLink (Western and Southern) and EastLink in Melbourne, Clem 7, Airport Link, Logan Motorway, Gateway Motorway in Brisbane and Cross City Tunnel, Sydney Harbour Tunnel and Bridge, M4, M5, WestLink M7, M1, M2 in Sydney are such key projects. Government failure to construct freeways to cater to the ever-rising traffic demand and congestion, especially using the allocations through central budgets has been solved by investment options, such as PPP or BOOT schemes. Furthermore, widespread belief that the private sector is inherently more
efficient than the public sector, and therefore builds and operates facilities at less cost than the public sector and the public sector, facing taxpayers resistance, may simply be unable to finance facilities that the private sector would be willing and able to undertake for profit (de Palma and Lindsey, 2000; Lay and Daley, 2002; Yang et al., 2002).

Under usual circumstances public resistance or non-acceptance of road user pricing is high (Holguín-Veras et al., 2006) and hinder the implementation of road user charges to manage congestion, but when it comes to new investment project, the public tends to accept it (de Palma and Lindsey, 2000). Otherwise, there will not be a freeway to use even with a direct cost. In other words, these projects are found to be a win-win situation where there is no obvious loser, provided charges cover all the costs, including congestion and environmental, and as far as users find it worthwhile to patronize the new road. In Switzerland, besides infrastructure, the toll price includes the costs associated with health care, damage to buildings, and noise. Further, a toll is applied to HGVs above 3.5 tonnes, and it is levied on all roadways, not just national motorways (Broaddus and Gertz, 2008).

One of the most critical issues concerning the development of a private toll road is the selection of its capacity and toll charges and the evaluation of the relevant benefits to the private investors, the road users and the whole society (Yang et al., 2002). The objectives of different stakeholders, mainly three parties in this context, are quite different and are often in conflict with each other. The objective of government is to maximize the benefit defined in terms of social welfare added to society. Private investors aim to maximize profits generated from the investment. Road users attempt to minimize the inequality of benefit distribution among the road users traveling from different origin-destination (O-D) pairs (Chen and Subprasom, 2007). In most cases, the toll system operator earns a share of the revenue stream as defined in its contract, but the government retains the power to make pricing decisions (Broaddus and Gertz, 2008). It is also clear that, in order for road pricing to fulfill its potential as either a transport demand management tool and/or a revenue generation mechanism, the actual tolls have to be set in accordance with economic theory (Holguín-Veras et al., 2006).
An important area of research is finding optimal tolls in transportation networks (Holguín-Veras et al., 2006). In Germany, the toll is calculated (for HGV) on the basis of distance traveled, number of axles, and emission class, based on a federal law (Broaddus and Gertz, 2008). On the other hand, the toll structures in the US are equally diverse, ranging from multi-tier price structures with frequent users, carpool, and time of day discounts to simpler structures in which the only differentiation is made on the basis of the number of axles per vehicle (Holguín-Veras et al., 2006).

It is argued that externalities produced from heavy vehicles are high at average speeds, with more stop-go conditions, and on rough surfaces. Noise, vibration, and emissions are such key externalities. The general public is under the impression that increased toll charges reduce the number of truck traffic on road system (Broaddus and Gertz, 2008), especially on freeways, which was found to be not really accurate according to José Holguín-Veras 2008, due to a diverse range of reasons. Increased toll charges do not make any significant change to truck traffic movements since at the end of the day there are no proper, practical alternative means to transport goods that are required to be transported, unlike in the case of private vehicle users shifting to public transport. Railway transportation could be considered as the mere substitute for truck transportation, but however, with existing facilities all over the world and its practical limitations such as door-to-door access and noise and vibration has a hinder expansion of such option as well. The negative impact of increasing toll prices for heavy vehicles could be that some of them may shift to the highway network, according to economic theory, especially at night times where traffic is less on such networks, but this could create significant environmental impacts or negative externalities. Therefore, it is important to consider the concept like city logistics when managing freight movement considering environmental and social impacts as well as economic impacts.

When determining urban freight policy it is also important to consider the effects for a number of stakeholders, including residents, carriers and receivers. City Logistics involves an integrated approach for planning and managing urban freight (Thompson and Taniguchi, 2001). When evaluating urban freight policies and schemes a broad range
of impacts should be considered including environmental and social as well as economic (Thompson, 2015).

Toll rates are typically set by the agencies that operate or own the toll facilities (Holguín-Veras et al., 2006) and in Melbourne as well. The rules or formulas by which these tolls are determined are not generally available to the public, but toll charges applicable for different vehicle types and different sections of the toll roads are readily available to the public. The objective of this paper is to present a comparison of toll charges that are being charged from different freight vehicles under different conditions, such as Time of the Day (TOD), infrastructure type, loading conditions, etc. The indirect costs of using alternative roads are also considered to enrich the analysis.

5.1.1 Toll roads in Melbourne

The Melbourne metropolitan area has two toll roads, namely the CityLink and EastLink, which were built as a PPP or BOOT and now in operation.

5.1.2 CityLink freeway

CityLink is a 22 km motorway in Melbourne which connects three major freeways, the West Gate, Tullamarine, and Monash. Toll collection is done electronically and this was one of the world’s first fully electronic toll roads (Lay and Daley, 2002). Both the Western and Southern links were opened to traffic in 1999 and 2000 respectively, more than 2.1 million so far vehicles registered to use this facility. CityLink Melbourne Limited is required to design, build, finance, operate and maintain CityLink for a period of 34 years ending on 14 January 2034 and then it will be transferred to State (VicRoads web site).

Different types of toll packages are available for users, mainly based on the frequency of usage. The general fair (the lowest) for frequent users is considered in this study where users have to maintain an online account with sufficient credit and a tag attached to the vehicle to use this package.

CityLink has different sections for toll charges based on entry and exits. However, type of infrastructure may have influenced the variation in toll charges (discussed in detail
later in this paper) such as bridges and tunnels. From North to South direction, section 6-8 is elevated, section 8-9 is a bridge structure (Bolte Bridge) and section 11-13 is a tunnel section (Burnley tunnel). When traveling from South-North direction the elevated and bridge sections remain the same. But the tunnel section is only from 17-11(Domain tunnel). Section 9-11 overlap with the West Gate Freeway and thus no toll charge is applicable.

Toll charges in CityLink vary based on the vehicle type and travel time (daytime between 6 am to 8 pm). There is four vehicle charging categories, namely, cars, light commercial vehicles (LCV), heavy commercial vehicles (HCV) and motorcycles. HCV include rigid trucks with three or more axels or over 4.5 tonnes GVM, buses with 13 or more seats including the driver as well as articulated trucks. Taxis are charged under a different scheme. Information and data used in this study were obtained from the CityLink web site. A more complex charging structure is applicable for CityLink compared to other toll roads. Charges are capped at different amounts (based on vehicle type and time of travel) to encourage long-distance travelers or to avoid charging very high amounts for traveling the entire section.
EastLink is a 39km freeway in Melbourne’s east connecting the Eastern, Monash, Frankston, and Peninsula link freeways that were built and opened to the public in 2008. EastLink cost 2.5 billion AUD to construct and has been operating as a toll road since its open for traffic. This road will be transferred to the client, the State of Victoria, after the concession period of 39 years, which ends in the year 2043 (VicRoads web site).

EastLink has a simple charging structure for users based on the road sections traveled and this paper only focuses on regular charges that are for frequent users with tags (lowest price). EastLink road is also facilitated with ERP, surprisingly no price
differentiation can be observed with time or direction of travel. Vehicles are categorized into 4 basic classes for charging purposes, similar to CityLink but these charges may vary. Toll charges for commercial vehicles are capped (a maximum amount to be paid) based on trip length and the maximum charge for an LCV is $9.50 and $15.74 for an HCV (EastLink website).

EastLink has a simple typical layout where entry and exit ramps are provided at each intersection for both directions, except in one or two cases. Apart from the Melba and Mullum Mullum Tunnels (1.6 km) in section 1-2, there are no major structures on EastLink freeway. However, at node 11, where it crosses the Monash Freeway, a cloverleaf interchange was constructed.

**Figure 0.2: EastLink map**

1- Springvale Rd  
2- Ringwood Bypass  
3- Maroondah Hwy  
4- Canterbury Rd  
5- Boronia Rd  
6- Burwood Hwy  
7- High Street Rd  
8- Ferntree Gully Rd  
9- Wellington Rd  
10- Police Rd  
11- Monash Fwy  
12- Princes Hwy  
13- Cheltenham Rd  
14- Dandenong Bypass  
15- Greens Rd  
16- Thompson Rd  
17- Peninsula Link & Frankston Fwy
5.2 Analysis and discussion

Toll roads in Melbourne charge different prices from freight vehicles based on type (LCV or HCV), time of the day, a geographic section of travel and facility types such as bridge, tunnel, elevated section or an ordinary road section.

There exist a spatial equity issue in the sense that the changes of the generalized travel costs of drivers traveling between different origin-destination (O-D) pairs may be significantly different when tolls are charged for using some selected links (Yang and Zhang, 2002). It can be argued that tolls should be in pro-rata with distance traveled since tolls are being charged for using a facility but not being used as a congestion charge. In CityLink, the tolls were set to maximize revenue (Lay and Daley, 2002) and different toll charges apply (not in proportion with distance) when traversing through different sections of the toll road. This could be due to different structural components of the toll road such as tunnels, bridges and elevated section, which cost more for construction compared to on the ground road. As a result, different toll charges are being imposed to recover the cost of investment.

Pavement damage is one of the main conditions considered when setting up charges for commercial vehicles in the world due to the obvious fact that heavy commercial vehicles vary in a large spectrum of loading categories which creates vast significant damage to the pavement. As a result, Equivalent Standard Axles Loads (ESAL) or a number of axles are being considered when setting up efficient toll prices for heavy vehicles along with space consumption (Holguín-Veras et al., 2006). But surprisingly, such application cannot be observed in Melbourne, especially when with an ERP system in operation.

Therefore, this study focuses on illustrating the variation in toll charges in CityLink and EastLink based on distance traveled and how it affects freight vehicles, and society considering various cost elements. Although this study is limited to HCV the approach may be used to model other truck traffic in order to minimize the total costs of freight vehicle movement in cities, which is not limited to the operational costs for freight vehicles.
5.2.1 CityLink

Figures 5.3 and 5.4 below depict the different toll charges calculated per km for HCV when various OD options are considered. This also shows the various day and night time charges in yellow and black lines respectively.

**Figure 0.3:** Toll fee per km on different sections of CityLink based on trip OD for HCV (N-S direction from Tullamarine to Monash)
Analysis of toll charges

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Figure 0.4: Toll fee per km on different sections of CityLink based on trip OD for HCV (N-S direction from Exhibition to Monash)

On the Western link, the maximum toll charge per km ($2.72 /km) applies when traveling from section 8-9 irrespective of day or night. This can be well explained by looking at the infrastructure type of this road section which is the Bolte Bridge. It can be assumed that, since the construction cost was high, higher toll charges are imposed. The next highest charge ($2.64 /km) is from the tunnel section (Burnley tunnel) during the day time, but slightly less during night time. Similarly, high toll charges are applicable when traveling from section 6-7, which is an elevated section, $2.41 /km day or night. Considering the cost of construction, it can be stated that these charge levels are rational, in other words, higher toll charges for expensive structures, but irrationality tends to occur when OD changes. For an example, when traveling from section 6-8, which is entirely along the elevated section, the charge was found to be $1.81 /km, lower than the charge from section 6-7, which is a similar type of structure. This is because the same charge applies when a vehicle enters from node 6 and exits from either node 7 or 8.

For the Southern link, surprisingly, the highest toll charge per km ($2.71/km) is charged from section 19-18, which is a bridge section over rail tracks. This is almost equal to the maximum charge on the Western link, Bolte Bridge section. Further, it can be noted that
when traveling from section 18-12 the charge is about $1.29/km and trucks continue to travel on section 12-13 (traveling from 18-13) the charge will go up to $2.35/km. Further, by observing the above two figures it can be stated that on Southern link the minimum charge per km is above $1, whereas the majority of the charges are scattered around $0.4-$1.0/km on the Western link.

It can be clearly seen that on CityLink (both Western and Southern links) the ratio between day and night charges for (same OD pair) is not consistent. Day/night charge per km ratio varies between 1.33 to 1.01 from case to case.

![Toll charge per km, based on the trip distance on CityLink for HCV (N-S direction)](image)

**Figure 0.5:** Toll charge per km, based on the trip distance on CityLink for HCV (N-S direction)

Figure 5.5 above shows the different toll charges that apply per km (both West and East links) based on the total trip distance traveled. It can be clearly seen that “all time” charges apply for shorter trips (trip length <10km) and day/night charges reduce with increased travel distance. Furthermore, it can be seen that high rates are being charged for shorter trips (less than 5km) in CityLink and the simple regression curve (logarithmic) drawn in Figure verifies this.

The cost of traveling can be calculated based on cost factors published by authors elsewhere based on their previous work (refer Yang et al., 2016 for more details) and a
summary is extracted and presented below in Table 5.1. Even though a separate cost summary Table (5.1) presented below, it should be noted that the figures in Table 5.1 were also developed based on the estimations presented in Chapter 4.

**Table 0.1: Summary of costs associated with truck operation (A$/km)**

<table>
<thead>
<tr>
<th>Truck Type</th>
<th>At 100km/hr-Freeway (free flow)</th>
<th>At 60km/hr-Highway (stop-go)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>VOC</td>
<td>VOT</td>
</tr>
<tr>
<td>LCV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Short</td>
<td>1.22</td>
<td>0.28</td>
</tr>
<tr>
<td>2 Axle Truck</td>
<td>1.19</td>
<td>0.28</td>
</tr>
<tr>
<td>3 Axle Truck</td>
<td>1.23</td>
<td>0.29</td>
</tr>
<tr>
<td>4 Axle Articulated</td>
<td>1.28</td>
<td>0.29</td>
</tr>
<tr>
<td>5 Axle Articulated</td>
<td>1.48</td>
<td>0.30</td>
</tr>
<tr>
<td>6 Axle Articulated</td>
<td>1.59</td>
<td>0.30</td>
</tr>
<tr>
<td>B Double</td>
<td>1.92</td>
<td>0.31</td>
</tr>
<tr>
<td>Double Road</td>
<td>2.23</td>
<td>0.31</td>
</tr>
<tr>
<td>Triple Road Train</td>
<td>2.68</td>
<td>0.31</td>
</tr>
</tbody>
</table>

(Source: Yang et al 2016)

Table 5.1 above depicts the summary of costs involved in truck operations, both direct and indirect, considering a number of parameters as described below. This table only consists of two sample speeds but detail information is presented in the original publication.

Vehicle Operating Cost (VOC) = f(fuel, speed, tire, maintenance, distance dep., time dep., interest, tax, insurance, registration, administration)

Value of Time (VOT) = f (drivers wages, allowances, working hours)

Environmental Cost (EC) = f (emissions, noise)

Social Cost (SC) = f (accident, congestion, infrastructure)
A case study was developed to study the travel cost between different OD pairs using CityLink as the base case and the highway route as the alternative. Table 5.2 below summarises the travel between different OD pairs, during the day time, traveling in a North-South direction using CityLink as well as the highway route in order to compare differences between two trips with respect to time and distance. Travel time (off-peak day time, without significant congestion) and distance traveled were obtained for selected OD pairs (not all OD combinations were considered for simplicity purpose) for comparison purposes using Google Maps. It is important to note that OD locations for this study were selected considering the accessibility to CityLink, not for the alternative routes. The additional cost incurred for using the alternate route was calculated based on the above equations in order to determine the trade-off between paying the toll or using an alternative road to complete a journey. Further, the calculations were limited to 3 axle trucks (one of the most common truck types in Australia), but no major variation was found with other vehicle categories as well.

Table 0.2: Comparison of travel using CityLink and an alternative route for 3-axle HCV (N→S dir.)

<table>
<thead>
<tr>
<th>Entry-Exit Node</th>
<th>CityLink</th>
<th>Alternative Route</th>
<th>Dif. in Cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>D (km)</td>
<td>T (min)</td>
<td>Toll ($) HCV</td>
</tr>
<tr>
<td>2-4</td>
<td>5.5</td>
<td>5</td>
<td>4.34</td>
</tr>
<tr>
<td>2-5</td>
<td>7</td>
<td>6</td>
<td>4.34</td>
</tr>
<tr>
<td>2-8</td>
<td>9.6</td>
<td>8</td>
<td>8.68</td>
</tr>
<tr>
<td>2-10</td>
<td>14.6</td>
<td>12</td>
<td>11.42</td>
</tr>
<tr>
<td>2-13</td>
<td>18.1</td>
<td>14</td>
<td>11.42</td>
</tr>
<tr>
<td>2-15</td>
<td>22.4</td>
<td>19</td>
<td>11.42</td>
</tr>
<tr>
<td>6-8</td>
<td>3.1</td>
<td>4</td>
<td>4.34</td>
</tr>
<tr>
<td>6-10</td>
<td>8.2</td>
<td>8</td>
<td>9.77</td>
</tr>
<tr>
<td>6-13</td>
<td>11.7</td>
<td>11</td>
<td>11.42</td>
</tr>
<tr>
<td>6-15</td>
<td>16</td>
<td>15</td>
<td>11.42</td>
</tr>
<tr>
<td>8-10</td>
<td>5.5</td>
<td>6</td>
<td>5.43</td>
</tr>
<tr>
<td>8-13</td>
<td>9.1</td>
<td>8</td>
<td>11.42</td>
</tr>
<tr>
<td>8-15</td>
<td>13.4</td>
<td>13</td>
<td>11.42</td>
</tr>
<tr>
<td>19-15</td>
<td>8.4</td>
<td>9</td>
<td>11.42</td>
</tr>
<tr>
<td>19-12</td>
<td>3.2</td>
<td>4</td>
<td>5.42</td>
</tr>
<tr>
<td>19-13</td>
<td>4.2</td>
<td>5</td>
<td>9.76</td>
</tr>
<tr>
<td>19-18</td>
<td>1.7</td>
<td>3</td>
<td>2.71</td>
</tr>
</tbody>
</table>

Notes: D- Distance, T-Time, VOC-Vehicle Operating Cost ($/trip), VOT- Value of Time ($/trip), Dif. in Cost=CityLink (VOC+VOT+Toll)-Highway (VOC+VOT)
A fundamental principle in transport states that tolls should be set so that the cost felt by drivers reflects the total cost they produce, including the economic costs and externalities (Holguín-Veras et al., 2006). Operation costs include vehicle operating costs (VOC) plus the value of time (VOT), whereas externalities produced are calculated by means of environmental and social costs (for more detail see Yang et al 2016). However, freight operators’ make their route decision based on simple economic theory to minimize their costs (Lay and Daley, 2002).

Table 5.2 shows that the distance traveled on alternative routes is sometimes less than CityLink but travel times are always found to be greater in all cases considered above. Having said that, it doesn’t mean that traveling on toll road always experiences less travel costs for users or vice versa. The trade-offs have been calculated considering the distance traveled per given trip, with time spent on respective routes in order to see which route costs more than the other based on a simple economic model. The last column in Table 5.2 denotes the direct cost difference between freeway and highway alternative (including toll charges). The analysis clearly shows that about 65% of the routes (highlighted in green) trucks would choose alternative roads over CityLink freeway based on their operating costs. Further, since these costs factors are not fully known to the operators and therefore all marginal cases may also fall into highway category (Yang et al 2016). Sometimes it argued that even travel time savings for freight vehicles are not an attractor for toll roads, but savings in operating costs are (Lay and Daley, 2002). If that is the case in the analysis, it favors more towards highway alternatives over freeways based on a simple economic decision.

Economic Costs (EC) and Social Costs (SC) produced by vehicles are together considered as externalities. Based on Table 5.1, freight vehicles produce less EC when traveling on highways due to the near optimum level of fuel consumption but the SC is higher. When both are considered together as externalities, it can be stated that trips on freeway produce less externalities compared to trips on highways for freight vehicles. In that case, when more freight trips are diverted to highways based on direct economic benefit, it produces more and more externalities which have to be born by other stakeholders.
This study considered times when there was assumed to no significant congestion on both the freeway and highway routes which may not always be the case in reality. Freeways mostly operate less than near capacity level, but highways tend to become congested at times. With the development of congestion the social cost increases, which makes the above-presented situation worst.

It is important to note that externalities are not a direct cost which has to be born by anybody out if their pocket but are costs incurred by society as a whole. Therefore, when freight vehicles make route decisions based on their direct costs of operation they tend to use the alternative routes in most of the cases over CityLink as explained above to complete their trip based on simple economic grounds. This creates massive external costs to society since highways can become congested and average running speeds are less compared to freeways most of the time.

5.2.2 EastLink

EastLink has a simple toll charging structure compared to CityLink and the road layout is also quite simple where there are entry and exit ramps at every node, for either direction of travel, except for few locations. There is no variation in charges based on the time of travel even though an electronic toll collection (ETC) system is in operation. It is widely accepted that the dynamic tolls are more efficient (Holguín-Veras et al., 2006) thus this is taken as an indication of toll policies are not at the most efficient level. Further for toll charges is also limited to 5 vehicle categories, similar to CityLink.

Figure 5.6 depicts the simple variation in toll charges being charged for HCV when travelling in the North-South direction (however there is no variation based on direction of travel in EastLink due to simple layout and simple charging structure) on EastLink and clearly indicates that different toll charge rate(s) (per km) exist for different sections.

It is obvious that high charges ($1.86/km ~ 1.65/km) in sections 1-2 or 1-3 are due to the presence of Melba Tunnel for 1.6 km and thus high toll charges may justifiable from an economic viewpoint. However, apart from that, there are no major structures along EastLink to justify the variation in toll charge rates, for an example on sections 9-10, 14-15 and 16-17.
Figure 0.6: Toll charge per km for each section for HCV (N-S direction)

Figure 0.7: Toll fee per km vs trip distance based on trip OD for HCV on EastLink

Figure 5.7 depicts the toll charge per km based on different OD pairs for HCV on EastLink. Due to the high price charged on section 1-2, all trips starting from node 1 have comparatively high charges (circled in the figure) but reduce when distance travel increases. It can be clearly noted that most of per kilometer charges are scattered...
around $0.50 to $0.75 range over the distance but tend to reduce slightly when the distance is reaching its maximum. The simple regression curve (logarithmic) shown in Figure 5.7 indicates that shorter trips are comparatively charged more than longer trips based on distance.

![Figure 0.8: Effective toll charge in EastLink section 4-5 based on trip OD for HCV](image-url)

Figure 5.8 depicts the different effective toll charges charged at section 4-5 on EastLink based on the trip OD. In other words, even though the theoretical charge for using section 4-5 for HCV is $1.05, the effective price paid (based on per km travel) by the HCV users may vary based on their trip length, which is based on their OD. The minimum charge could be for traveling this section is $0.76 and the maximum could be $1.84. However, based on their trip OD one of the above-depicted charges may apply effectively. This is a sample analysis considers only section 4-5, nevertheless similar variations can be seen in all sections due to variation in toll charges over the distance traveled.

Table 5.3 below shows a sample exercise carried out using a number of OD pairs to compare travel costs for heavy vehicles when 2 different routes are used (similar to CityLink study above). Namely, EastLink and an alternative route (highways and arterial roads) to travel from a set origin to a set destination. The analysis was only done for 3 axle trucks, for North-South direction, day time only, for simplicity purposes. The vehicle cost rates are taken from Table 5.1.
From this analysis, it can be noted that for some OD pairs toll charge plus operational cost (VOC+VOT) is high compared to operational cost on highway (highlighted). It should be noted that when performing this analysis origin and destination nodes are considered closer to the freeway (EastLink) to favor easy access to freeway and thus freeway case is always privileged.

If freight vehicles tend to use alternative routes simply based on the comparison of direct costs and toll charges, over 35% of the trips considered would use the highway alternative. However, it can be seen that the majority of them are starting (origin) at section 1 where toll charges are high due to the tunnel section. Apart from that, no major shift to alternative route can be seen in EastLink unlike in CityLink.

### Table 0.3: Comparison of travel using EastLink and an alternative route for 3-axle HCV (N-S dir.)

<table>
<thead>
<tr>
<th>Entry-Exit Node</th>
<th>D (km)</th>
<th>T (min)</th>
<th>Toll ($)</th>
<th>VOC ($)</th>
<th>VOT ($)</th>
<th>D (km)</th>
<th>T (min)</th>
<th>VOC ($)</th>
<th>VOT ($)</th>
<th>Diff. in Cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-3</td>
<td>5</td>
<td>5</td>
<td>7.24</td>
<td>5.41</td>
<td>2.39</td>
<td>5.3</td>
<td>7</td>
<td>7.40</td>
<td>3.35</td>
<td>4.30</td>
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<td>1-5</td>
<td>8.1</td>
<td>6</td>
<td>9.34</td>
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<td>2.87</td>
<td>8.3</td>
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<td>11.49</td>
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</tr>
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<td>17.8</td>
<td>20</td>
<td>24.49</td>
<td>9.56</td>
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<td>18.6</td>
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<td>15.74</td>
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<td>20</td>
<td>24.75</td>
<td>9.56</td>
<td>9.29</td>
</tr>
<tr>
<td>1-13</td>
<td>25.3</td>
<td>17</td>
<td>15.74</td>
<td>29.82</td>
<td>8.13</td>
<td>23</td>
<td>27</td>
<td>31.76</td>
<td>12.91</td>
<td>9.02</td>
</tr>
<tr>
<td>1-15</td>
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<td>19</td>
<td>15.74</td>
<td>32.27</td>
<td>9.08</td>
<td>27.8</td>
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<td>29</td>
<td>35.57</td>
<td>13.86</td>
<td>10.69</td>
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</tbody>
</table>
5.2.3 Comparison of toll policies in Melbourne and it’s impacts

Table 5.4: Comparison of toll charges in Melbourne based on infrastructure type

<table>
<thead>
<tr>
<th>Infrastructure Type</th>
<th>CityLink ($/km)</th>
<th>EastLink ($/km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regular Road Section</td>
<td>0.54~1.32</td>
<td>0.41~1.31</td>
</tr>
<tr>
<td>Tunnel Section</td>
<td>2.64 (Burnley)</td>
<td>1.86 (Melba &amp; Mullum Mullum)</td>
</tr>
<tr>
<td>Elevated Section</td>
<td>2.41 ~ 1.81</td>
<td>Not Available</td>
</tr>
<tr>
<td>Bridge Section</td>
<td>2.72 (Bolte)</td>
<td>Not Available</td>
</tr>
</tbody>
</table>

Table 5.4 presents a summary comparison of toll charges on two tollways in Melbourne based on infrastructure type. For regular sections, the minimum charge in CityLink is slightly higher whereas maximum remains the same. In tunnel sections again CityLink has higher charges compared to EastLink and a further comparison of toll rates are presented in Figure 5.9.

Figure 5.9 depicts the toll charge (per km) variation along the trip distance for two major toll roads in Melbourne, CityLink, and EastLink. At a glance, a significant disparity in the charging structure can be observed from the graph where EastLink toll charging structure is more rational compared to CityLink over the distance, which is represented by the rate of change of each curve (0.894 vs 0.071). CityLink tends to charge a very high amount for short distance travel (coefficient is 3.0789) compared to EastLink (coefficient is 0.8219). But when distances increase CityLink tends to charge lesser amounts compared to EastLink for trip lengths over 15km.
When goodness of fit ($R^2$) is considered, it shows how well the line is fit with given data. Very strong fitness can be observed in the CityLink curve but a poor fit can be observed in the EastLink curve. This is mainly due to the significant variation in toll charges when using the tunnel and few other sections as highlighted previously.

Table 5.5 shows analysis carried out to investigate the trade-off between how the selection of freeway route over highway route by heavy commercial vehicles will impact on society due to the externalities produced. Three scenarios are presented. Scenario one depicts the external costs produce by HCV on a freeway, usually running at 100km/hr. Scenario 2 depicts an HCV running on a highway at an average speed of 60km/hr (little or no congestion) and scenario 3 depicts a typical case on a highway where HCV is running at an average speed of 45km/hr (somewhat congested). The “Total” Column shows the total externalities (EC+SC) produced for each case and “Increase as a %” shows the percentage difference from the freeway scenario.

Table 0.5: Sample calculation

<table>
<thead>
<tr>
<th>Heavy Truck Type</th>
<th>At 100km/hr Freeway (free flow)</th>
<th>At 60km/hr Highway (stop-go)</th>
<th>Increase as a %</th>
<th>At 45km/hr Highway (stop-go)</th>
<th>Increase as a %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>EC</td>
<td>SC</td>
<td>Total</td>
<td>EC</td>
<td>SC</td>
</tr>
<tr>
<td>3 Axle</td>
<td>0.44</td>
<td>0.13</td>
<td>0.57</td>
<td>0.35</td>
<td>0.30</td>
</tr>
</tbody>
</table>
This analysis shows how freight vehicle operators make their decision based on direct cost, which is affected by toll charges and thus mostly favor the highway route. However, such decisions are purely based on direct costs with no externalities are considered. Therefore, this analysis highlights that when more and more trips are diverted to highways, how significant the external costs are with developing congestion. Even if highway speed remains at 60km/hr the externalities are 6%-17% higher compared to the freeway, which further rises significantly when speed is reduced on highways due to congestion. Therefore, charging higher toll charges to maximize benefit for the service provider may cause huge social costs to be incurred by society unknowingly.

### 5.3 Chapter summary

This study analyses different toll charging mechanisms on Melbourne tollways with respect to freight vehicles in order to identify trade-offs. Firstly, a disparity between the two toll charging schemes was found and secondly, disparities were found within the same facility which may not be able to be justified based on the cost of infrastructure provision. Toll charges on CityLink were found to be high on short distances and dilute over distance, whereas toll charges on EastLink found to be more consistent over the distance. Comparison of toll charges over savings (travel time and operational cost reduction) revealed that CityLink toll charges are marginally high over savings and EastLink tolls are more identical.

When externalities produced by large vehicles are considered it is very clear from the study that trips on freeways produce very less externalities compared to the same trip using highways and conditions are worst when congestion develops. However, when determining toll charges externalities seem not been considered and thus trucks avoiding toll roads produces significant costs to the society.
Chapter 6

Survey Data Collection

6.1 Introduction

Freight transportation has received more attention than before in Victoria, Australia, due to the rapid growth expected in freight volumes in the near future (Productivity Commission, 2017; Transport for Victoria, 2018). Demand for urban freight transportation is expected grow rapidly between 2014 to 2051 and priorities have been set by the government to achieve an efficient, safe and sustainable freight movement in cities (Transport for Victoria, 2018). Road transportation being the main freight transportation mode in Australia (Brodie et al., 2009) more attention is paid on road freight and heavy trucks. Due to the limited availability of unutilized land, the choices for new infrastructure development has been limited and as a result, the costs of new transport structures have risen rapidly (Productivity Commission, 2017). Therefore, more efficient utilization of existing transport infrastructure is vital and policies to improve transport efficiency within existing constraints have been examined (Productivity Commission, 2017). Among the few priorities declared by the government, one of the sub-priority is to, “Align future toll road contracts with Government’s freight efficiency and congestion management objectives” (Transport for Victoria, 2018). This objective is perfectly in line with the main objective of this research; which is,
'Determining optimum toll prices for freight vehicles in urban context’. Overall, this thesis looks at how toll charges can be used to optimize economic, social and environmental costs considering multiple stakeholders to provide a more sustainable solution (more details can be found in Chapter 1). The approach specified by this thesis addresses the government objective of improving freight efficiency while managing congestion by means of proper toll road contracts.

When making a policy decision it is important to consider the cost and benefits to all stakeholders. The acceptability of a policy by stakeholders and sustainability of a policy would rely upon the net benefits to each stakeholder. However, the decision-making power in the supply chain is usually limited to one dominant stakeholder. Identifying such a dominant player in the supply chain and planning a policy aimed towards receiving their acceptability is important for policymakers. Because there is more and enough evidence from the past that some policies have not accepted by users/stakeholders and have been limited to papers. The acceptability of transportation policies and related issues has been discussed in detail in the literature review section (please refer to Chapter 2 for more details).

Therefore, the objective of this chapter is to understand ‘who is the main decision-making body?’ and ‘how specific decisions are made?’ in toll charges related freight activities in the urban conditions. This understanding would be more helpful when formulating policies and making them more acceptable by stakeholders. Research has been carried out in other parts of the world to identify the decision makers (in the supply chain) and to understand the behavioral patterns in the urban freight industry. However, the Australian context could be different from others due to geographical, demographical and economic variations. A survey was carried out in the city of Melbourne in order to collect the information.

This survey has three sections covering various stakeholder objectives and their behavioral response to various scenarios in urban freight movement. These conditions are selected based on the literature to understand the Australian context. In general, Part A and Part B of the survey investigates the decision-making behavior of Victorian freight users. Part C of this survey is intended to find the remaining stakeholders
objectives, other than freight users, such as the government, residents and toll operators.

Finally, the outcome of this survey is to understand the Australian urban freight movement and to support the urban freight movement model developed considering economic, environmental and social factors. Results from the survey are also used in the MAMCA analysis to find the best solution (among alternatives) considering multiple stakeholders. This Australian specific information would help investigate more suitable and sustainable toll schemes and policies for urban freight in Melbourne, Australia.

6.2 The survey

According to Richardson et al., (1995), “The conduct of a survey is not an informal procedure. Rather, it should follow a series of logical, interconnected steps which progress towards the final end product of the survey”. Figure 6.1 depicts the modified version of such logical steps described by the Richardson et al. incorporating the University of Melbourne survey guidelines (additions are shown in blue color).

6.2.1 Preliminary planning

The main objective of this survey is to understand Australian urban freight movements and to support the urban freight movement model developed considering economic, environmental and social factors. This Australian specific information would help to investigate more suitable and sustainable toll schemes and policies for urban freight in Melbourne, Australia.

Since urban freight movement has multi-stakeholder involvement there is a necessity to gather information from key stakeholders to provide any sustainable solution for city logistics. Thus, specific survey objectives were formulated reviewing existing information from the literature.

In this preliminary planning process, the time available to complete the survey and the availability of human resources were the two major constraints received attention. In addition, attention was paid to the University of Melbourne guidelines on, ‘how to
Survey data collection

conduct a survey?’ and respective ethics approval. This ethics approval process is a time consuming and tedious process at the University of Melbourne and may usually require a few rounds of revisions before the approval is given. As a result, it was decided at the beginning to maintain a strict policy on a number of questions asked, the content of the questions (as per the University of Melbourne guidelines), and how data will be recorded, maintained and destroyed after some time.

Specific survey objectives are;

✓ To collect information regarding the key stakeholder objectives, their rankings and relative weightings.
   This information will be used for the MAMCA as well.

✓ To collect the information regarding the route preferences of freight users (between tolled and highways) given the toll charge, travel times, and distance for different route options.

✓ To collect the information regarding the decision-making process (who and how) of freight users under various behavioural conditions.
   Different behavioural conditions include route selection, toll road selection and congestion avoidance by freight operators and relative importance of decisive factors for each selection.

Due to the involvement of multiple stakeholders in this study and subsequently a large number of questions to be asked, the main survey is divided into 3 parts as Part A, Part B and Part C. More details of different parts of the survey are given under ‘Sample Design’ sub-heading.
Figure 0.1: The modified transport survey process

Source: (Richardson et al., 1995)
6.2.2 Selection of survey method

As mentioned under the preliminary planning section, the selection of the survey time frame was critical since the overall time duration (for thesis completion) is restricted by the School of Engineering. Considering the rigid time frame and less human resource available it was decided to conduct an online survey which would save more time compared to a paper-based survey (e.g. sending the survey forms, collecting the survey forms and manual data entry).

Sampling technique is critical in a survey to collect accurate information. At the same time, resources available, mostly the time and money are constraints which determine the sampling technique. However, better the sampling technique and larger the sample size, higher the cost and time need to spend for the survey. Since transportation studies are often associated with large populations, which is the case in this survey in Melbourne, the selection of a good sample is not an easy task given the limited resources. On the other hand, considering the nature of the freight industry it is very difficult to approach a representative/owner or user from a trucking company or an individual truck user who is willing to take part in a survey, which may greatly affect the survey response rate. Therefore, it is more practical to deviate from random sampling techniques to a non-random sampling technique in this survey to collect the required responses. Thus, the quota sampling technique is mostly used in this survey, sometimes mixed with expert sampling. More details on individual sampling techniques used for the different parts of the survey are as follows:

Part A of the survey was emailed (online link) to members\textsuperscript{1} of the Victorian Transport Association (VTA) with the help of Mr. Peter Anderson, CEO of VTA. In addition, the survey was sent to some selected members in Engineers Australia database with the help of Mrs. XYZ and to some random operators found in the field (while doing survey Part B and to some known operators).

\textsuperscript{1} VTA members represents over 800 employers/businesses that support transport, logistics and freight related services with in Victoria, Australia.
Many large and medium size transportation and logistics companies are members of VTA but single owner small sized companies or individuals who operate a single truck are not members of VTA most of the time. As a result, the survey responses are more from medium to large size operations and less from ancillary truck operations. Thus, there is a possible bias of survey results representing medium to large sized freight operations. On the other hand it’s practically difficult to reach those ancillary operators in Melbourne, which is time consuming. Therefore, much easier approach was taken to reach respondents in this part of the survey.

Part B of the survey was mainly conducted off-roads including loading/unloading bays in the CBD, wholesale markets and fuel stations with truck rest areas. Since all truck types and truck companies may not use above mentioned facilities there could be possible bias collecting data from a sub-set of a population. However, such bias has been reduced by choosing multiple locations at multiple time frames and by collecting more responses. Again, the sites were selected at the convenience of the surveyor considering the constraints discussed above.

Part C (Q2): Relevant officials (Transportation planners or traffic engineers) from Transport for Victoria, City Councils (Dandenong, Monash, Knox, Maroondah, Maribyrnong, and Casey) and VicRoads were the main participants. Officials from Transport for Victoria and VicRoads were reached using personal contacts. City Council officials were contacted first over the phone and then an appointment made to explain the survey. Then the online link to the survey question was emailed.

The possibility for bias response has been reduced by conducting the survey among many government organisations. However, responses from higher officials in the government level (e.g. ministry level) would have lead to more accurate results.

Part C (Q3): There are two major toll roads in the City of Melbourne, namely, CityLink and EastLink, operated by TransUrban and ConnectEast respectively. Both roads were built under PPP and both roads are operating well at present condition. The survey was sent to both operating companies but both companies refused to respond to the survey due to their data privacy policies in control. As a result, no responses were received for the question 3 in Part C of the survey.
Part C (Q4): This fourth question was designed for residents or road users and the main participants for this question was members of the Maribyrnong Truck Action Group (MTAG) (MTAG, 2016). The survey question (online link) was emailed to the membership through the secretary, Mr. Martin Wurt. Since all the members in the MTAG group have a very good idea about truck movements, it’s negative impacts and the government’s interference to their problems, etc. It is believed that better feedback was received for this survey question from MTAG members. However, by choosing members from a specific group there is a possibility for a biased response. On the other hand responses received from such acknowledged group of people have more weight compared to a response given by a random resident who may not have such understanding about the problems under discussion.

6.2.3 Sample design

As mentioned above this survey is divided into 3 parts based on the key stakeholders and specific survey objectives. Part A of the survey is specially designed for fleet managers or freight operators who would take a collective decision on behalf of their entire fleet behavior. Part A of the original survey is given in Appendix 6a.

Part B of the survey is a Discrete Choice Experiment (DCE) to capture the sensitivity of toll charges with regard to travel times and travel distances when it comes to route choice selection. Part B of the original survey is given in Appendix 6b.

Part C of the survey is designed to investigate the various objectives and their priorities among the key stakeholders involved in city logistics, except for freight operators. The key stakeholders were identified from the literature and attention was paid to three remaining key stakeholders in this part of the survey. The government, toll operators and residents (including non-freight road users) were the remaining key stakeholders. One question for each stakeholder type was given inquiring about their objectives. All possible objectives were listed under each question and respondents were asked to allocate 100 points as explained in the next section. The objective listing was done by a group of professionals representing government, industry and the academic field. Any ambiguity or misrepresenting objectives were revised during the pilot survey before the
commencement of the main survey. Part C of the original survey is given as Appendix 6c.

6.2.4 Survey instrument design

6.2.4.1 Part A: For Fleet/ Freight Operators

The first two questions of the survey were intended to cover the ownership type of the fleets, fleet composition and line of business (owner-driver, for-hire or both) along with commodities being transported. The third question was aimed at understanding priorities in freight operators’ objectives, which is very useful when making policy decisions. In fact, response to this question was used to calculate the weights for stakeholder objectives for Multi-Agent Multi-Criteria Analysis (MAMCA) presented in Chapter 10. Remaining questions in this part of the survey is focused on route selection, toll road usage, congestion avoidance and delivery times.

Most of the survey questions in this part were designed to look at a specific problem or behavior highlighted in the city logistics literature. Most of the literature is either from Europe or USA and thus there is a gap determining whether the same behavior is applicable to the Australian context for not having the same geographical conditions, population size, or population dispersion. As a result, the intended purpose of this part of the survey is to understand how such behavior is applicable to Australian urban context as mentioned earlier. Each question was designed and reviewed by professionals in the industry before the pilot survey was carried out. More details and associated research background for each question is presented along with the analysis.

From question 3 to 8, respondents were asked to allocate 100 points among the listed options for each question. This way the options are ranked and at the same time options are relatively measured by assigning a weight. For example, let’s assume that given question has 4 options as shown below.

Example question:
Let’s assume if someone responded as the ‘Possible Answer’ shown above, it means that option A is ranked one, option C is ranked two, option B is ranked three and option D is ranked last. At the same time, it means that options A is ten times important than option D and option C is 2 times important than option B. Further, option B is three times important than option D and so on. Therefore, this point allocation system reveals to us not only the ranking of the set of options given but their relative measure on a points scale as well.

6.2.4.2 Part B: For Freight Operators/Drivers

The initial questions of this part of the survey collect general details of the respondent such as vehicle type and commodity type(s) being transported in general. Because it’s evident from the literature such general details determine the heterogeneity of freight vehicles and intended to validate with Australian data. Afterward, eight discrete choices were given to each respondent randomly picked out of the 2 blocks available. Details about how the survey design was conducted are described in the Methodology section (Chapter 3).

In both blocks shown in the Appendix 6b, there are 8 choice sets in each block and each choice set is comprised of 3 options, namely, ‘Highway’, ‘Toll Option A’ and ‘Toll Option B’ to select. Apart from the highway option, two toll options are used to reduce the total number of responses required for this part of the survey. Three attributes are used in this design where attribute levels are the same for two toll roads. A subset of such attribute levels is used for the highway option to make all options realistic (e.g.
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distance/travel time is more than 120kmph does not represent a realistic scenario) and to avoid dominant answers (one option having all attribute levels favorable compared to other two options).

Attributes and attribute levels for Toll Option A & B are: Travel Time {12 min, 10 min, 7 min, 5 min}, Travel Distance {14 km, 12 km, 10 km, 7 km}, Toll Charge {A$ 10, A$ 8, A$ 5, A$ 3}. For the highway option: Travel Time {12 min, 10 min, 7 min, 5 min}, Travel Distance {14 km, 12 km, 10 km}, and there are no toll charges.

Since Part B of the survey was mainly targeted at freight drivers, the survey was mainly conducted off-road including loading/unloading bays at CBD, wholesale markets and fuel stations with truck rest areas. Figure 6.2 below shows some pictures taken while the survey was in progress.

Given the complexity of the survey questions and factors related to the respondents (drivers), such as the physical status of the driver (fatigue, tired), the time they can spend on a survey (based on their schedule) and human factors were the real challenges lessened the participation for this survey. However, after visiting some places many times and talking to more truck drivers have pushed up the participation numbers. In total 97 drivers responded², 51 to block A and 46 to Block B. As a result, the total number of choice responses received was 1,552 (97*8*2). The analysis of this part of the survey is also presented under the analysis section below.

² These are the good responses received. There were few incomplete survey forms, mostly marked without paying serious attention. Those responses were discarded.
6.2.4.3 Part C: For Government Officials, Toll Operators and Residents/Road users (non-freight)

In this part of the survey, each stakeholder was given only one question listing their objectives (possibly all). They were asked to allocate a total of 100 points among the listed objectives considering the relative importance of all objectives, similar to the explanation given under Part A. More details about the survey structure and respondent’s feedbacks are given under the analysis section.
6.2.5 Pilot survey

Before the pilot test, all 3 surveys (especially Part A and C) forms were discussed with a small number of key experts in the government sector, truck association and academics in order to find out any possible mistakes, errors and misleading questions. After a couple of rounds of revisions, the survey forms were finalized. The pilot test of the survey Part A was conducted with few members at a small group meeting held at the Victorian Transport Association (VTA) head office in Port Melbourne. There were about 8 members and the objectives and other important information was explained to the members before the survey was given. For some question’s answers were given promptly but there were few questions led to minor changes in the survey form. A good response was received for the pilot survey without any major comments and thus survey form was finalized for the main survey.

Part B of the survey was initially tested with few known truck drivers and there was no considerable feedback from the respondents other than a few subjective comments. Similarly, Part C of the survey was also tested with a few known people who have an idea about freight movement and relevant issues. The feedback was good and thus no changes were made to the original survey forms.

Changes from the Pilot Survey

- This survey was planned to be a paper-based survey initially but after the pilot survey, it was changed to an online form (Part A and Part C only). The main reason behind this change is the points allocation and total have to be 100. Online survey forms are more capable of handling such complex situations with minimum errors.
- Notes were added to the survey explaining some terminologies (e.g. externalities)
- The font size of Part B of the survey was increased
- Few wording were omitted from Part C of the survey to make it more simple

6.2.6 Ethics approval

This is the step added to the Richardson et al. survey process in order to incorporate the guidelines stipulated by the University of Melbourne code of conduct for research. “This
Code of Conduct prescribes standards of responsible and ethical conduct expected of all persons (academic staff, students, technical and other support staff) engaged in research in The University of Melbourne” (Uni Melb, 2018).

Since this survey is a standard survey with minimal risk which has involvement with people only, the approval from the Human Research Ethics (HRE) committee was sufficient. Therefore, all relevant documents were submitted (e.g. Project Application Form, Plain Language Statement, Consent Form and the Final Survey Document) in advance and after one revision the approval was granted by the HRE committee. The application to the HRE has covered most of the survey steps discussed in this Chapter and the ‘Plain Language Statement’ given in Appendix 6d explains about the survey, benefits and risks, results and data.

6.2.7 Administration of the Survey

Administration of this survey was not complicated since the researcher was the main surveyor most of the time except for Part B. Several postgraduate university students provided assistance for the main surveyor to complete the Part B of the survey. Short training was provided to those post-grad students before the commencement of the survey. This short training program was mainly consisting of the questionnaire details and interviewing technique which is more helpful to eliminate errors and to receive good responses.

Since Part A and Part C of the survey was designed to be delivered online the administration of the survey became easy due to the tools available in the survey software package used. Nevertheless, survey progress monitoring was done on a weekly basis and reminders were sent frequently to increase the response rate.

Finding out proper locations where surveyor can talk to truck drivers under safe conditions was a tough administrative task carried out for Part B of the survey. Information regarding locations were gathered from talking to locals and people who have done similar surveys in the past, as well as from known truck drivers. Once locations were identified, getting permission to enter those premises (e.g. Fruit and vegetable market in Epping and fuel stations) and how to maintain safety on site were
the two remaining administrative tasks for the survey. This resulted in writing letters to obtain permission, making prior appointment for a private tour and wearing illuminative jackets to improve visibility (improve safety). Printing survey forms (Part B) and taking care of the completed survey forms from the site to the office were the next level of administrative duties carried out for Part B of the survey. In addition, attention was made to make sure both blocks (Blocks I and Block II) are used equally.

6.2.8 Data coding, data editing and data correction

Data processing for part A and Part C of the survey was straightforward due to the online survey software package used and the points allocation system used. However, there is no way an individual questionnaire form can be edited on site, but supervisory editing was carried out at the office.

**Part A:** In total 102 operators responded to the survey but some of the responses were incomplete and had to be disregarded. Finally, 71 good responses were left for analysis.

**Part B:** Since this was a paper-based survey, both field data editing and supervisory editing was carried out and as a result, few responses were discarded.

**Part C:** There were 16 completed responses out of 18 for question 2 of the survey, which was designed for the Government /Local Authority officials. Question 4 of this survey, which was designed for residents or road users received about 126 responses, out of which 94 good responses were considered for analysis.

Once the processing was completed the data were translated into labeled categories suitable for computer processing. Since points allocation technique was used for most of the questions in Part A and Part C of the survey the same points were used for the coding purpose. For the other multiple option questions coding was required to extract the results. The online survey package has summarised the survey results using text which were converted to matrix format with binary codes for further analysis.

Since Part B of the survey was paper-based all data had to be entered to the computer manually. A simple template was created using MS EXCEL to enter the data using binary
Survey data collection

codes and later converted into different formats for analysis requirements using MATLAB.

For all data entered, verification was done manually on a random basis and consistency checks were done throughout the analysis. There were few missing data for some questions in Part A and Part C of the survey. Such conditions were identified and excluded from the respective analysis.

6.2.9 Data analysis

6.2.9.1 Part A

Heterogeneity in the freight industry is one of the main difficulties faced by transport planners. When proposing a policy to different types of freight users (running LCV or HCV) who has different attributes (e.g. vehicle operating cost, the value of time, willingness to pay, etc.) may react differently (de Magalhães, 2010; Holguín-Veras and Cetin, 2009). Therefore, to start with, the classification based on the ownership was questioned by the respondents and the distribution is presented in Figure 6.3.

![Pie chart showing percentages of respondents from different categories.]

**Figure 0.3:** Respondents from different categories

‘For-hire’ percentage in this sample was found to be higher (45%) compared to both ‘owner driver’ percentage (24%) and ‘both’ percentage (who’s partially hiring their
vehicles) (31%). Out of 31%, respondents in the ‘both’ category 10% of the respondents hire their vehicles more than 80% of the time. Therefore, this sample has more representation from ‘for-hire’ category than the ‘owner driver’ (ancillary) category.

Figure 6.4 below depicts the number of trucks owned under different ownership types by respondents. Irrespective of the ownership type, owners tend to operate large fleets having more than 10 trucks whereas having 2-5 trucks in their fleets found to be little unusual in this sample.

![Figure 0.4: Fleet ownership vs fleet size of respondents](image)

Table 6.1 below shows how respondents use different truck types to transport different commodity types. For transportation of general freight and other commodity types, all truck types are being used according to the survey and for remaining commodity types there is a tendency towards using larger trucks (6 axle articulated and B-Doubles) for transportation. A study by Hassall and Thompson, (2011) have found that 2 and 3 axle rigid trucks, super B Doubles, A Doubles, and semi-trailers are potentially having high productivity gains in urban freight transportation. According to the survey results, 2 axles and 3 axles rigid truck usage are comparatively less according to this study but B Doubles and semi-trailers (6 axles articulated) are used somewhat often. Thus, it can be
stated that the Performance-Based Standard (PBS) scheme (for more information about PBS refer to Thompson and Hassall, 2014) is not quite yet implemented in Australia.

**Table 0.1**: Truck type usage to transport different commodities by respondents

<table>
<thead>
<tr>
<th>Commodity Type / Vehicle Type</th>
<th>Short</th>
<th>2 Axle</th>
<th>3 Axle</th>
<th>4 Axle</th>
<th>3 Axle Articulated</th>
<th>4 Axle Articulated</th>
<th>5 Axle Articulated</th>
<th>6 Axle Articulated</th>
<th>B-Doubles</th>
<th>Road Train</th>
</tr>
</thead>
<tbody>
<tr>
<td>Food (Refrigerated)</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>7</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>8</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>Food (Non-refrigerated)</td>
<td>3</td>
<td>5</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>10</td>
<td>16</td>
<td>3</td>
</tr>
<tr>
<td>General Freight</td>
<td>10</td>
<td>14</td>
<td>5</td>
<td>16</td>
<td>15</td>
<td>7</td>
<td>8</td>
<td>25</td>
<td>41</td>
<td>12</td>
</tr>
<tr>
<td>Construction or Raw Materials</td>
<td>3</td>
<td>6</td>
<td>3</td>
<td>6</td>
<td>3</td>
<td>4</td>
<td>11</td>
<td>14</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Petroleum/Chemical Products/Liquids</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>Other Manufactured Products</td>
<td>4</td>
<td>7</td>
<td>3</td>
<td>4</td>
<td>6</td>
<td>3</td>
<td>4</td>
<td>13</td>
<td>19</td>
<td>6</td>
</tr>
<tr>
<td>Waste</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>6</td>
<td>2</td>
<td>0</td>
<td>1</td>
<td>4</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>Other Commodity</td>
<td>17</td>
<td>18</td>
<td>10</td>
<td>12</td>
<td>14</td>
<td>11</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>11</td>
</tr>
</tbody>
</table>

Figure 6.5 below depicts the freight operators’ response to their individual objectives prioritized based on the cumulative points for each objective. Percentages on top of each column show the overall mean value (all types of fleet ownerships together) for each objective. Figure 6.6 below depicts a more detailed version of the responses received for objectives, classified by owner type. For each question there could be a difference in the way the points are allocated for each option by ownership type because the heterogeneity of the freight operators may have an impact on the decision made. Therefore, the fleet type and mean values for each ownership type and for the overall condition are presented along with their standard deviation values in Table 6.2. This has been done for all the questions in this survey and results are presented in the same table to make it clear.
Overall, the cost minimization objective was found to be the most common objective followed by the travel time minimization. However, it can be observed from the figure that for owner-drivers cost minimization is the most important objective while for for-hire operators travel time minimization found be the main objective. This is due to the
fact that for-hire operators can make multiple trips if time is saved, but for owner-driver operators they don’t have such intentions (since they transport their own goods only) but to reduce cost which has to be paid out of their pockets. Reliability is also received a reasonable level of response (17%) but road safety has received an unexpectedly lower response rate. Reduction of externalities seems to be the least concerned objective amongst the freight operators. Therefore, any new policy on improved road safety or reducing externalities has to go a long way to receive user acceptance.

Since cost minimization was found to be the main objective among freight operators, freight operators would like to use any route which will minimize their costs irrespective of travel time or other factors. In other words, it can be argued that toll routes (routes with toll roads) are not the most preferred route for freight vehicles since toll roads are mainly for travel time saving but not for cost saving. However, since travel time has some impact on cost, these two factors cannot be considered fully independent.

Table 0.2: Mean and standard deviation for options given in the survey by fleet ownership

<table>
<thead>
<tr>
<th>Fleet Ownership</th>
<th>Owner Driver</th>
<th>For-hire</th>
<th>Both</th>
<th>Overall</th>
</tr>
</thead>
<tbody>
<tr>
<td>Survey question and options</td>
<td>Mean [SD]</td>
<td>Mean [SD]</td>
<td>Mean [SD]</td>
<td>Mean [SD]</td>
</tr>
<tr>
<td><strong>Freight operator’s objective</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Who does the route selection</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Company/ Manager</td>
<td>40 [32]</td>
<td>31 [31]</td>
<td>34 [34]</td>
<td>34 [32]</td>
</tr>
<tr>
<td><strong>Factors considered for route selection</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Survey data collection

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle operation cost</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Road type/ Turning restrictions/</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Toll road usage**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>When customer requested</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Always</td>
<td>65 [46]</td>
<td>62 [40]</td>
<td>64 [45]</td>
<td>64 [42]</td>
</tr>
<tr>
<td>Never</td>
<td>6 [24]</td>
<td>0 [1]</td>
<td>0 [0]</td>
<td>2 [12]</td>
</tr>
</tbody>
</table>

**Strategies to avoid congestion**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Shift to off-hour deliveries</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Who decides the delivery time**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Driver</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Receiver/ Sender</td>
<td>53 [42]</td>
<td>60 [38]</td>
<td>57 [37]</td>
<td>57 [38]</td>
</tr>
<tr>
<td>Other</td>
<td>0 [0]</td>
<td>1 [2]</td>
<td>0 [0]</td>
<td>0 [1]</td>
</tr>
</tbody>
</table>

When ownership based mean values given in Table 6.2 are compared, ‘owner driver’ type have more preference towards road safety and focus less on either cost minimization or travel time saving compared to other two categories. On the other hand, ‘for-hire’ and ‘both’ types are more concerned about travel times and cost factors.
comparatively. ‘For-hire’ operators are more concerned about travel time minimization over cost minimization probably because they want to make more turns as much as they can for any given day.

Overall freight operators are more sensitive to their travel costs and travel times and less sensitive to safety, reliability or externalities. As a result, any new policy or new TDM strategy needs to focus on one of the above-mentioned key objectives in order to receive a good compliance rate.

When looking at the mean values for different objectives under various fleet ownership types, it shows some differences as discussed above. To test the significance of these differences two non-parametric tests, namely, the Kruskal Wallis test and Chi-square test were carried out to determine the statistical significance of various ownership types over the individual objective. The outcome from the Kruskal Wallis test and the Chi-square test applied to question 3 is presented below.

\[ H_0: \text{All populations are distributed in the same way} \]

\[ H_1: \text{At least one of the populations is differently distributed} \]

**Table 0.3:** Outcome from Kruskal Wallis and Chi-Square tests applied to ownership type and cost minimization objective

<table>
<thead>
<tr>
<th></th>
<th>Owner Driver</th>
<th>For-Hire</th>
<th>Both</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sum R )</td>
<td>590</td>
<td>1075.5</td>
<td>883</td>
</tr>
<tr>
<td>( n )</td>
<td>17</td>
<td>32</td>
<td>22</td>
</tr>
<tr>
<td>( \frac{\sum R}{n} )</td>
<td>20476.4706</td>
<td>36146.8828</td>
<td>35440.4091</td>
</tr>
</tbody>
</table>

\[ H = 0.11211852 \]

\[ \text{Chi Inv (0.01,2)} = 9.21034037 \]

\[ \text{Chi-square p value} = 0.73241 (>0.05) \]

\[ H < \text{Chi Inv}. \text{ Therefore, the null hypothesis is accepted in both tests} \]

From both statistical test results, it was found that irrespective of the ownership type freight operators’ response towards cost minimization objective is the same. Therefore,
there is no heterogeneity with respect to freight ownership when their objectives are concerned as found in this sample. This may be due to sample bias towards the ‘for-hire’ category as explained above and the presence of more large players in all ownership category (having more than 10 trucks) (see Figure 6.4).

Figure 6.7 below summarises the response received for route selection options by freight operators and Figure 6.8 summarises the decisive factors for route selection. Overall, the majority of the route selections were done by the driver (46%) followed by the company/manager (34%). About 10% just use the traditional route they used to travel and about 9% use advanced software to find the optimal route for the delivery(s). However, whether drivers still use their experience/knowledge to decide the route or are they use any readymade software package like Google Maps is not known. With this greater flexibility shown in route selection choice, there is a greater chance to influence the truck operators to change their road usage behavior with some incentives such as low charges during off-peak as proposed by Forkenbrock, (2005).

![Figure 0.7: Route selection by freight operators](image-url)
The most important criteria for route selection among those listed is delivery/departure time which explains the receiver dominance in the delivery process as discussed in many past studies. Further, when looking at the individual mean percentages obtained by ownership type (Table 6.2) it reveals that “for-hire’ truck owners are more concerned (29%) towards delivery/departure times compared to other two categories, 25% and 20% for ‘owner-driver’ and ‘both’ respectively.

Trip distance and vehicle operation cost and toll charges are also considered to a certain level whereas externalities produced are given very less priority in such decision making. Trip distance factor is mostly concerned by ‘both’ ownership type and vehicle operation cost was least considered by ‘for-hire’ type according to mean values depicted in Table 6.2. Even though there is no evidence to prove there is a statistical significance with respect to decisions made under various ownership types.

The toll road usage by freight operators was tested in the next question and the responses are summarised in Figure 6.9. Only 64% of the operators said that they were always using the toll roads. Meaning there is a large percentage of trucks (36%) whose

---

**Figure 0.8:** Factors considered when deciding routes by operators

The diagram shows the cumulative points for different factors and ownership types. The factors are ordered by their importance:

- **Externalities produced** 1.1%
- **Road type/ Turning restrictions/ Road curfew** 9.5%
- **Delivery/ Departure time** 24.9%
- **Commodity type/ Loading** 5.6%
- **Reliability** 8.6%
- **Toll charge** 14.6%
- **Vehicle operation cost** 16.9%
- **Distance** 18.8%

Owner Driver

For-hire

Both

---

For more detailed analysis, please refer to Table 6.2.
primary selection is not toll (quality) roads. The present high toll prices for trucks on CityLink and EastLink could be the governing factor for such an outcome. Further increases in toll prices may reduce the numbers in the ‘Always’ category. Less than 20% (in total) responded that they are using toll roads either only when a customer requested (5.6%) or when the truck is loaded (6.6%) or during congested times (6.4%). ‘both’ ownership type is more tempted to use toll roads when a customer requested and during congested times whereas ‘for-hire’ owners are more responsive to toll roads when trucks are loaded. Only ‘owner-driver’ category responded to never use toll roads option and the overall percentage is less than 2%.

A study carried out by Holguín-Veras et al., (2005) indicated that trucking companies did not consider tolls when making route and delivery time decision, which is found to be different in Melbourne context. At the same time Holguín-Veras, (2011) has mentioned that only a handful of industry segments are sensitive to tolls, but such detailed information cannot be revealed from this survey and thus the validity of the statement cannot be tested.

In conclusion, this survey confirms that there is a significant negative perception of the current toll charges in Melbourne. Therefore, there is a necessity to look at ways to bring more freight vehicles to toll roads (quality roads) since they produce more externalities and create other negative impacts while driving on sub-standard roads.

There are few on-going discussions in the literature regarding the decision-making body or in other words trying to find out who is the dominant player in the supply chain. This is an important factor to know because successfulness of any policy introduced in city logistics will be determined by such a dominant party based on the benefits they receive. Thus, finding answers to the prevailing questions such as ‘who has the decision-making power for the delivery time?’, ‘Is there flexibility for carriers (freight operators) to decide their own delivery times?’, ‘Whether off-hour deliveries are an option to daytime congestion?’ are critical.
Based on the studies carried out in other countries (e.g. U.S.A. and Europe) researchers have concluded that receivers are the strongest player in the supply chain and do not wish to change the manner in which they receive their goods (dell’Olio et al., 2017). Especially when there is an additional cost for receivers, receivers would not like to show any flexibility in goods receiving time.

However, the heterogeneity of the commercial sector may act differently to the general perception. New goods distribution policies such as Off-Hour Delivery policy (OHD) and distribution system using an Urban Distribution/ Consolidation Centres (UDC or UCC) have received some positive response irrespective of the additional cost involved (dell’Olio et al., 2017).

Considering all the points mentioned above, questions 7 and 8 were included in the survey to gain some idea about how it works in the Australian context. Responses are summarised in Figures 6.10 & 6.11.
Survey data collection

Figure 0.10: Strategies used by operators to avoid congestion periods

About 15% have the flexibility to change their delivery time, among which ‘owner-driver’ category shows more flexibility over other two ownership types. Similarly, about 11.8% of the freight operators showed some flexibility to shift to OHD where ‘owner-driver’ group was again dominant. About 20% responded as they can change the start time (of the delivery) to avoid congestion. This decision was led by ‘for-hire’ category. This probably means that freight operators (mostly ‘for-hire’ type) have no choice to change the delivery time instead of making the trip early and waiting for the delivery to avoid congestion. Load sharing and using consolidation centers (UCC) to avoid congestion are equally popular among freight operators, but overall mean percentages are not significant (around 4% each). The load sharing option is more popular among ‘for-hire’ category and usage of UCC is mostly preferred by ‘owner-driver’ compared to other ownership types. Nearly one-fifth of the operators are willing to take toll roads to avoid congestion compared to other given options such as load sharing, usage of UCC, shifting to OHD, etc. Among those operator’s ‘owner-driver’ group shows the least interest towards using the toll roads to avoid congestion. Majority of the respondents (27.3%) do nothing to avoid congestion and this is something that needs further investigation.
Because congestion is a negative externality that needs to be minimized and thus the majority of the freight operators having no option to avoid congestion means there is a serious problem in city logistics in Melbourne.

Urban Consolidation Centres (UCC) are considered as a practical solution to reduce traffic and environmental problems in cities (Aljohani and Thompson, 2018; Browne et al., 2011; Lin et al., 2016; Taniguchi, 2014). Similarly, load sharing is also an innovative solution to city logistics and practices in many countries including Europe and Brazil (de Magalhães, 2010; Quak, 2012). However, when looking at the high percentage of respondents selecting ‘do nothing’ option and low response percentages for UCC and load sharing options, Australia seems to be still lacking in either innovative thinking and awareness or infrastructure to implement such innovative practices. In conclusion, Australia is not using any innovative approaches in city logistics as other countries. Therefore, its high time to think more about executing some innovative approaches in Australia for sustainable freight transportation in the future.

**Figure 0.11**: Who decides the delivery time for operators

Overall, answers to the above question revealed that there are plenty of openings that need to be filled to shape the urban freight transportation in Australia, which requires more focused studies to identify specific problem(s) in city logistics and application of innovative solutions with better awareness.
Question 8 provides a much straightforward answer to the decision-making agent for deliveries in the Australian context. From the results, it is clear that either receiver/sender decides the majority (57%) of the delivery times where the company/manager has some autonomy (36%) to make such a decision. Drivers are having much less opportunity (7%) to make a decision on delivery times.

Considering the fact that receiver has a greater influence on delivery times, past researchers have looked at policies fostering switching truck traffic to off-hours by encouraging the receivers to accept OHD by providing different incentives (Holguín-Veras et al., 2007). Even though this initiative seems to be a good and viable option at glimpse it may have two sides. The request to make OHD will provide the opportunity to carriers to avoid the congestion (savings from vehicle operation cost), avoid tolls or fewer toll charges (if nighttime tolls are discounted) but increase driver costs due tonight working hours. The greatest problem in such an initiative is more freight vehicles will be avoiding toll roads at night since highways are free to travel, with higher speeds at night time. The condition could be worst when there night time tolls are applied like in Melbourne. Overall, noise and other externalities associated with OHD is a major obstacle to implement such an initiative (Holguín-Veras et al., 2005). Therefore, planners must be careful when looking at such policies by primarily looking at only direct outcomes.

Finally, by looking at the overall response made by Melbourne freight operators it can be concluded that Australian freight movement is also somewhat similar to the world context where receivers are the major decision maker with respect to delivery times and thus transportation/freight planners should be aware of this when proposing new initiatives to reduce congestion or improve city logistics.

6.2.9.2 Part C

6.2.9.2.1 Government/local authority

There were 16 completed responses for question 2 of the survey, which was designed for the government officials. Relevant officials (Transportation planners or traffic engineer) from Transport for Victoria, City Councils (Dandenong, Monash, Knox,
Maroondah, Maribyrnong, and Casey) and VicRoads were the main participants. The summarised responses are given in Figure 6.12.

<table>
<thead>
<tr>
<th>Objective</th>
<th>Cumulative Points</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduce impact on residents and environment</td>
<td>16%</td>
</tr>
<tr>
<td>Reduction of road maintenance cost</td>
<td>12%</td>
</tr>
<tr>
<td>Road safety</td>
<td>29%</td>
</tr>
<tr>
<td>Network usage optimization</td>
<td>11%</td>
</tr>
<tr>
<td>Reduction of freight users operation cost</td>
<td>10%</td>
</tr>
<tr>
<td>Return to road investors (toll roads)</td>
<td>2%</td>
</tr>
<tr>
<td>Sustainability</td>
<td>8%</td>
</tr>
<tr>
<td>Congestion control</td>
<td>12%</td>
</tr>
</tbody>
</table>

**Figure 0.12**: Government objectives towards freight transportation and their priorities

Based on the response from government officials it’s clear that the government’s main objective is to improve road safety and their least concern is about the payback to road investors. Most of the other objectives received almost equal response comparatively with a slightly higher rate for reducing impacts on residents and the environment.

It is surprising to see the low response rate received for the ‘Return to road investors’ because in theory it is one of the government’s main responsibilities to protect the investors (otherwise the whole PPP will collapse) and toll prices are determined collaboratively. According to Hensher (2018), the toll prices are prescribed by the government (possibly at a higher level) and indexed over time by the consumer price index. This provides logical reasoning for why the government officials at an operational level do not really care about returns to the investors, since its pre-arranged.

On the other hand, this pre-determined toll prices (linked to the consumer price index) are making sufficient returns for the investors and thus may be the reason why investors
are not keen to explore options to optimize user benefits or to minimize negative impacts.

By receiving more or less the same percentage for all the other objectives (except road safety and return to investors) it is clear that the government officials are trying to safeguard all stakeholders in a reasonable manner. For example, the reduction of freight users’ operation costs also received a similar response as congestion control and sustainability.

6.2.9.2.2 Toll operators
There are two major toll roads in the City of Melbourne, namely, CityLink and EastLink operated by Transurban and ConnectEast respectively. Both roads were built under PPP and both roads are operating well at present. The survey was sent to both operating companies but both companies refused to respond to the survey due to their data privacy policies. As a result, no responses were received for the question 3 in Part C of the survey.

6.2.9.2.3 Residents/road users
Figure 6.13 depicts the summarised results based on residents’/road users’ response.

![Figure 6.13](image)

**Figure 0.13:** Residents and road users’ objective with respect to freight transportation
Air quality has received the maximum priority (29%) among all the objectives for residents. Secondly, both less noise and improved safety were ranked with 22% each. However, it is important to highlight that residents/road users do not really pay attention to the toll charges as well as the travel times. But some concern has been shown towards congestion reduction. This again illustrates that car users (non-freight vehicle users) are not quite concerned about the toll levels even though the present toll charges are found to be high in Melbourne. This was the argument brought up in toll elasticity discussion where car users either have a higher willingness to pay or to use highways, but freight vehicles do hesitate to pay extra money for high tolls.

In conclusion, new policies need to be looked at three major aspects with regard to residents, namely, improved air quality, noise reduction and improving road safety. In reality, there is a number of initiatives that have been taken in order to reduce emissions or to control air pollution from truck exhaust such as ‘Cleaner Freight Initiative’ launched in Melbourne, Australia recently. When it comes to road safety, it receives good attention from all policymakers since road safety is in the priority list of all transportation modes, and not limited to freight transportation. This can be proven by looking at the government response to the survey where road safety has been ranked as one of their primary objectives. However, there is no such initiative has been taken towards noise control in Melbourne (for more information regarding transportation noise, its impacts and remedial measures readers can refer to: Andersson and Ögren, 2011; Cik et al., 2012; Day et al., 2006; Forkenbrock, 1999). Thus, there is a gap to fill by understanding how important noise control is and how it can be reduced or controlled especially for heavy vehicle movements.

6.2.9.3 Part B

Table 6.4 shows the mixed logit results obtained from R software.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Coefficient</th>
<th>Std. Error</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>TT</td>
<td>-0.218516</td>
<td>0.025199</td>
<td>&lt;2e-16 ***</td>
</tr>
<tr>
<td>TL</td>
<td>-0.270920</td>
<td>0.020005</td>
<td>&lt;2e-16 ***</td>
</tr>
</tbody>
</table>
Therefore, the values for travel time and travel distance can be calculated as:

\[
v_{TT} = \frac{\beta_{TT}}{\beta_{TL}} = \frac{-0.218516}{-0.270920} = 0.81 = 81 \text{ cents/min}
\]

\[
v_{TD} = \frac{\beta_{TD}}{\beta_{TL}} = \frac{-0.046347}{-0.270920} = 0.17 = 17 \text{ cents/km}
\]

Based on the model results the value of travel time can be calculated as 81 cents per minute, which means A$ 48.6 per hour. This rate is more than the time value of money obtained considering the wages of freight drivers (See Chapter 4 for more details) and this rate is more appropriate to consider as the willingness to pay factor in the main model. However, it is important to note that model results show that travel time (TT) and toll charges (TL) variables are very significant but travel distance (TD) variable is less significant based on the real preferences made by the respondents. This may be due to the less value perceived by the freight drivers per kilometer (17 cent per km). As a result, for the traffic assignment method, which in the lower level scenario in this thesis as described under Chapter 3, the travel distance can be neglected, and traffic assignment can be purely done considering travel time.

6.2.10 Presentation of results and tidying-up

Once the data has been collected and the analysis has been completed it feels like the project is finished which is not the case according to Richardson et al., (1995). Communication of the survey results to the participants and other effective parties and data storage is critical for the completion of a survey project. The answers to these questions in this survey were clearly addressed in the Ethics Approval Form set (Plain Language Statement) and as follows.

✔ Will I hear about the results of this project?
The results will be published in journal articles, conference papers, and included in this thesis. Apart from that, the results will be electronically sent to any participant upon their request.

✓ **What will happen to information about me?**

According to University procedures, the data gathered by this project will be retained for five years after the date of the last publication which includes the results. Data will be destroyed after this period and no one else can possibly access the data other than the project team during this time.

### 6.3 Chapter summary

This chapter is mainly focused on providing additional and supportive information to the main model of the main study discussed in this thesis. The objectives of the key stakeholders involved in this toll optimization problem were found using the survey described in this chapter and used as an input to evaluate the optimum toll options using multi-agent multi-criteria analysis. In addition, other information collected through the survey was used to compare the urban Australian context with the world findings. This information is very useful when making policy decisions. The outcome from the discrete choice experiment was used to determine the freight driver’s willingness to pay toll charges to use toll roads in the urban context. This information is a very prominent ingredient for traffic assignment and no such data can be found in the literature as well. Therefore, this chapter fill the gaps in the toll optimization model development process by providing urban Australian (Melbourne) specific information.
Chapter 7

Determining Optimum Toll Charges for Freight Vehicles Considering Multi-Stakeholder Objectives in Urban Conditions

7.1 Introduction

Public perception is that toll charges are determined in collaboration between the investors and road authorities but apparently, this rarely occurs outside academic studies. Nevertheless, it was found in the literature that higher toll charges are placed in many facilities all over the world or disparity exists between the classes of heavy vehicles (Holguín-Veras et al., 2006; Holguín-Veras and Cetin, 2009; Perera et al., 2016). It is common to make such toll decisions based on economic modeling with explicit rationale but sometimes it can be noted that these do not favor other stakeholders, such as the general public or residents. With vast experience in handling public-private
partnership (PPP) projects, Norwegians have now realized the importance of other stakeholder objectives towards more sustainable transportation. As a result, it’s now in the scope of project evaluation methodologies to consider socio-economic aspects rather looking at financial issues only (Odeck, 2017).

Modeling toll setting can be undertaken by considering it as a hierarchical problem where investors decide on the toll price and users react to such prices in the most optimal manner which could involve them minimizing their travel time/cost. This leader-follower relationship is non-cooperative, and leaders cannot completely control the behavior of users but can influence users by imposing various toll charges. Toll optimization and related user behavior has been studied by researchers in the past, such as, (Chen et al., 2004; Chen and Bernstein, 2004; Holguín-Veras and Cetin, 2009; Koh et al., 2009; Lawphongpanich and Hearn, 2004; Rus and Romero, 2004; Verhoef, 2002; Yan and Lam, 1996), mostly considering financial factors. However, beyond these two types of decision-makers, there are other key stakeholders in this system such as the general public in the form of residents who are more concerned about environmental and social aspects.

It is a very common practice that with high toll charges vehicles tend to avoid toll roads (McKinnon, 2006; Quak and van Duin, 2010), especially freight vehicles, consequently producing high externalities. This has become a major hazard for residents and their concern against emissions and noise around the local neighborhood is growing over time. Therefore, it is essential to consider all stakeholders’ objectives when determining toll charges for freight vehicles to improve the sustainability of urban transportation in the future.

City logistics is based on the concept of total optimization (Taniguchi and Thompson, 2014). Various stakeholders in the freight vehicle movement have different goals and objectives which may conflict with one another. Since City logistics look at overall system optimization, all stakeholder objectives are taken into account, but less priority is given to individual objectives. City logistics considers the triple bottom line approach, which is evaluating systems based not only on economic but also social and environmental aspects. As mentioned above, freight vehicle route choices are based on their individual
costs, and when tolls are present users tend to avoid toll roads which will lead to high environmental and social costs being produced, which have been neglected by route choice modeling in the past and present. As a result, residents and other stakeholders have to bear the costs of freight transport in terms of poor air quality, high noise levels, unsafe road conditions, more congestion, etc. The concept of system optimization encompasses minimizing direct costs (economic) as well as externalities (social and environmental). It is used in this study to develop a methodology for sustainable freight transport systems in urban context considering toll effects. Thus, this study looks at evaluating the trade-offs between these multiple objectives and how optimum conditions can be achieved.

The rest of this chapter is structured as follows. Section 2 briefly reviews the related background and Section 3 outlines the methodology developed in this study. Results are presented and analyzed in Section 4 and Section 5 presents a summary of the study.

7.2 Background

In this model development, researchers have paid much attention to understanding various toll charging mechanisms and their impacts. Since all road links on a road network are not tolled, the first best pricing is not really practical, and a more realistic version known as second-best pricing was introduced. Under this second-best pricing technique, only a subset of links of a network are tolled (Chen et al., 2004) and this has been studied heavily in the past. Second best toll optimization under various conditions has been studied by a number of researchers (Koh et al., 2009; Lawphongpanich and Hearn, 2004; Verhoef, 2002), while optimal tolling with multi-class users was studied by (Chen and Bernstein, 2004; Holguín-Veras and Cetin, 2009). In addition, tolls and related issues have been discussed recently, including competition between private toll roads (de Palma and Lindsey, 2000), eliminating queuing on tolled links by selectively imposing time-varying tolls on a road network (de Palma et al., 2005), advanced pricing and rationing policies for large-scale multimodal networks (Gentile et al., 2005), optimal road tolls under conditions of queuing and congestion (Yan and Lam, 1996), an optimal toll design model with network travel time reliability (Li et al., 2008), private financing
and optimal tolls (Rus and Romero, 2004) and the toll design problem with stochastic route choice (Chen et al., 2004). However, there have been few studies which have looked at vehicle heterogeneity and respective tolls on network conditions considering economics as well as externalities.

Heterogeneity of freight vehicles is important to consider when considering, the damage trucks cause on pavements, which is an exponential relationship in terms of axle loads (Chou, 1996; Dodoo and Thorpe, 2005; Fowkes et al., 1992; Ren et al., 2016; Sathaye et al., 2010), the impacts on social and environmental systems (Lignier, 2011)(Perera et al., 2016; Swan and Belzer, 2010; Yang et al., 2016) and decision making power with respect to delivery times, loading condition and route selection (Holguín-Veras, 2008; Holguín-Veras et al., 2007) compared to passenger vehicles or light vehicles. As mentioned above, limited research has been carried out to understand the relationship between freight vehicle heterogeneity and optimal toll levels in the past. Many studies have looked at how passenger vehicles respond to toll charges but only a very limited number of studies have been undertaken with respect to freight vehicles (Holguín-Veras, 2010). Therefore, freight vehicles seem to be often penalized, ending up with them either paying high charges or using alternate roads. Before reaching any conclusions, it is important to look at how freight vehicles would respond to toll charges.

Usually, freight vehicles produce more externalities compared to light vehicles, but these vary substantially depending on road type and speed (Swan and Belzer, 2010). Therefore, tolls can lead to more costs for society in terms of emissions, noise, air quality (environmental factors), road safety, crashes and congestion (social issues). However, Holguín-Veras, (2010, 2008); Holguín-Veras et al., (2007); Quak and van Duin, (2010) have suggested that freight vehicles do not respond to toll charges as car users do and further it was found that freight carriers are not the sole decision-maker regarding delivery parameters (e.g. time and mode). As a result, trying to shift freight vehicles to the night time by just offering discounts on tolls does not seem to be a successful strategy in practice.
7.3 Model development

As mentioned in Chapter 3 this problem has two levels, upper and lower levels. The upper level describes the role of policymaker, which is usually the government, who tries to minimize three main objectives considering all key stakeholders. The first objective is to minimize total user costs (including toll cost)\(^3\) as depicted in equation (1). The second objective is to minimize social costs and the third objective is to minimize environmental costs as depicted in equation (2) and (3), respectively. The return from toll charges is not considered as an objective at the upper level but considered as a constraint. For more information, please refer to Chapter 3 in this thesis.

One of the objectives in the upper level is to estimate externalities produced by freight vehicles, but there is no such comprehensive model available at the moment to quantify (in monetary terms) all aspects of it, especially in the Australian context. Therefore, the next step is to develop a model based on available data which can be used to estimate direct and indirect costs (externalities). This task has been accomplished and presented in Chapter 4.

It is important to understand that all these externalities were converted into dollar terms under prevailing conversion rates (which are highly subjective with time, e.g. carbon price over the last decade) mainly for the purpose of understanding of magnitude, which is sufficient to illustrate the impacts. As a result, these different cost values are not addable because each externality represents a qualitative feature as well as the assumption of perfect substitutability is not valid when considering social or environmental objectives (Neumayer, 1999; Wu et al., 2009a). In other words, noise costs cannot be compensated over congestion costs, even though the cost values (A$) are the same, but they are qualitatively different. Furthermore, humans (and all other living species) sensitivity to the environment can be quite different from person to person and place to place, as a result, impact estimation is a subjective process. Thus, too much reliance on final cost figures is not recommended but still, numbers are used

\(^3\) The toll cost is usually not considered as a direct cost since it’s a transfer cost between two parties in the same problem. However, in this context toll costs are included in user costs since we are looking from each stakeholder’s individual perspective.
to evaluation and comparison purpose and to understand the significance. Therefore, this study has emphasized multi-objective optimization where trade-offs can be clearly seen between three different objectives, user costs, environmental costs and social costs.

### 7.4 Results and discussion

The Elitist NSGA II (Deb et al., 2002) was used to determine the optimum toll values considering the trade-offs among all three objectives. Real number coding was used in the elitist NSGA II optimization, where a chromosome consists of four bits with each bit representing a toll charge for one type of vehicle. Here, a population size of 200, with a cross-over rate of 0.8 and a mutation rate of 0.05 was used with 5,000 generations to arrive at near Pareto-optimal solutions for both case studies. These parameters were decided based on a sensitivity analysis of GA parameter values. The final Pareto-optimal solutions were generated from ten runs with ten different random seeds to ensure near-optimal solutions were obtained. The toll revenue constraint given in equation (8) was relaxed to understand IRR with respect to each solution on the Pareto front (no limits for IRR has been set).

Since all three objectives considered in this study are measured in dollar terms it is possible to convert the multi-objective optimisation problem into a single objective optimisation problem using the weighted sum method to combine three objective functions into one function. However, the conversion will loss important trade-off information and lead to insufficient solutions (Wu et al., 2013). In addition, the conversion will lead to a single solution, reducing the flexibility in the decision-making process as discussed in section 3.2. Therefore, a genuine multi-objective approach is sued in this study to understand the nature of the trade-offs among user costs, environmental costs and social costs. For demonstration purposes, the three extreme solutions (i.e. the minimum user cost, minimum environmental cost and minimum social cost) from the Pareto-optimal front are presented in Table 7.1 for both the hypothetical and real-world case studies.
**Table 0.1**: Details of the extreme optimal solutions obtained for each objective under two case studies

<table>
<thead>
<tr>
<th>Solution</th>
<th>Toll Charge (A$/km) Car, 2-axle, 4-axle, 6-axle</th>
<th>Objective Value*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>User Cost (A$)</td>
<td>Environ. Cost (A$)</td>
</tr>
<tr>
<td>Hypothetical Network</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Min. User Costs</td>
<td>0.00, 0.00, 0.00, 0.00</td>
<td>76,361</td>
</tr>
<tr>
<td>Min. Environ. Costs</td>
<td>1.41, 1.46, 0.00, 0.00</td>
<td>85,588</td>
</tr>
<tr>
<td>Min. Social Costs</td>
<td>0.31, 0.10, 0.00, 0.02</td>
<td>78,370</td>
</tr>
<tr>
<td>Real Network</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Min. User Costs</td>
<td>0.00, 0.00, 0.00, 0.00</td>
<td>879,560</td>
</tr>
<tr>
<td>Min. Environ. Costs</td>
<td>0.33, 0.02, 0.00, 0.00</td>
<td>936,784</td>
</tr>
<tr>
<td>Min. Social Costs</td>
<td>0.57, 0.15, 0.02, 0.01</td>
<td>977,744</td>
</tr>
</tbody>
</table>

*Note:* these cost values are not addable since these cost elements are not perfectly substitutable

From the results shown in Table 7.1, for both case studies, user costs (operation costs plus tolls) are minimum when toll charges are zero. This may not be an intuitive result; as although operation costs can decrease with toll charges due to the network effect, but the marginal reduction in operation costs is less than that in toll charges. As a result, the zero-toll scheme has become the minimum user cost toll scheme in both cases.

When environmental costs are at the minimum, all heavy trucks (4 axles and 6 axles) are not charged tolls, whereas light vehicles (cars and 2 axle trucks) are charged more to achieve such an optimal condition (one extreme point). This confirms that heavy vehicles produce more externalities, especially when running on sub-standard roads or under disruptions to traffic flow. With less toll charges more heavy vehicles remain on the toll roads (quality roads). Similar to the minimum environmental cost solutions, the solutions with the minimum social costs have heavy vehicles being charged less compared to light vehicles.

In order to evaluate the toll revenue expected for each solution, IRR is calculated for comparison purposes. IRR is one of the top project evaluation technique not only in Australia but also in many countries of the world (Truong et al., 2008). According to Truong et al. (2008), the cost of capital in Australia is between 5-6% and therefore any toll scheme producing IRR above this limit can be considered profitable.
Optimum toll for multi-stakeholders

The IRR values obtained under different optimization solutions are quite different for the two case studies. There are more solutions on the Pareto curve for hypothetical network having IRR over 10% but comparatively fewer points on the Pareto curve obtained from the real network. The main reason behind this differentiation is the different traffic demand conditions implied on the two networks and the availability of alternative routes and capacities. Since the real network is loaded based on real demand conditions the toll revenue and the respective IRR values can be considered as accurate. Therefore, in real network, both minimum environmental costs solutions and the minimum social costs solution generate profits from the investment while minimum user costs solution generate negative profits due to zero toll revenue. From Figures 7.1 to 7.6, it can be observed that for both network studies toll schemes with similar IRR values are clustered than scattered. This means that there is a pattern for change in IRR with respect to the other three objectives and the solutions are more realistic.

As mentioned above, since this is a multi-stakeholder problem, all stakeholders’ objectives need to be considered to provide a sustainable, yet an effective solution. As a result, a Pareto-optimal solution (an optimal solution set for each network) were found, leaving a group of optimal solutions to the decision maker to choose one as the final toll scheme considering the present stakeholder demands. Figures 7.1 to 7.6 depict the pair wise trade-offs among the three objectives obtained for hypothetical and real network, respectively. As mentioned above, each point shown in the Figures represent a toll scheme (i.e. toll charge for cars, 2 axles, 4axles and 6 axle vehicles) which is not dominated by any other point (toll scheme). Therefore, any point can be chosen by the decision maker as the best toll scheme considering other factors such as government policy, etc.
**Figure 0.1**: Pair wise trade-off between environment costs and user costs objectives for hypothetical network

**Figure 0.2**: Pair wise trade-off between environment costs and social costs objectives for hypothetical network
Figure 0.3: Pair wise trade-off between social costs and user costs objectives for hypothetical network

Figures 7.7 and 7.8 depict the 3D view of the Pareto fronts obtained for the hypothetical and real network respectively. For each solution point (i.e. toll scheme) on the Pareto front considering the three objectives, the IRR value was calculated to understand the acceptability of such schemes from the investors’ point of view. Based on the cost of capital, four IRR value ranges were used to cluster the optimal solutions obtained for more clarity. The four IRR categories are: IRR less than 0% or negative IRR (blue diamonds on Figures 7.1 to 7.8), IRR between 0% and 5% (orange triangles on Figures 7.1 to 7.8), IRR between 5% and 10% (green dots on Figures 7.1 to 7.8) and IRR above 10% (purple squares on Figures 7.1 to 7.8). From the investor's point of view toll schemes having an IRR less than 5% (cost of capital in Australia) have a very high chance of being rejected, and all the other toll schemes with IRR’s above 5% should be accepted technically. The suitable IRR (or IRR range) can be decided by the decision-making authority (i.e. the government within the PPP agreement) based on financial factors, such as market rate of return for similar investments and risks undertaken.
Figure 0.4: Pair wise trade-off between user costs and environment costs objectives for real network

Figure 0.5: Pair wise trade-off between environment costs and social costs objectives for real network
Optimum toll for multi-stakeholders

In this three-objective minimization problem, the environment costs versus social costs and environment costs versus user costs results (Figure 7.1 and 7.2) shows clear trade-offs with a clear pattern between the corresponding two objectives for the hypothetical network. However, the patterns are bit scattered for the real network (Figure 7.4 and 7.5). When we look at the user costs vs social costs results for both case studies (Figure 7.3 & 7.6) a linear relationship can be observed between the two objectives. The main reason behind this relationship is both user cost and social cost are bound together by fuel consumption. The main contributor (in dollars) to social costs is congestion cost, which has a direct relationship with fuel consumption. The higher the congestion, the higher the fuel consumption is for any type of vehicle. Similarly, the main contributory cost element for user cost is also fuel cost. As a result, both social costs and user costs are co-related via fuel cost.

User costs and IRR have a clear connection via toll revenue. Toll revenue is considered as a user cost element while the same toll revenue is considered as the only income source for IRR calculation. As a result, when toll revenue increases, both IRR and user costs increase as illustrated in Figures 7.3 and 7.6. Lower environmental costs were achieved with higher IRR and vice versa, as depicted in Figures 7.1, 7.2, 7.4 & 7.5. This may be counter-intuitive, as it is often expected that lower environmental costs will be

**Figure 0.6:** Pair wise trade-off between social costs and user costs objectives for real network
achieved with a reduction in IRR due to the fact that heavy trucks avoid toll roads in high IRR conditions (high toll charges). However, when taking a closer look at the toll schemes on the Pareto front with high IRR rates it can be seen that heavy trucks either have no toll charge or very little toll charge compared to light vehicles and the revenue is mostly generated through the toll charges from light vehicles.

![Figure 0.7: Pareto-optimal points for hypothetical network](image)

**Figure 0.7:** Pareto-optimal points for hypothetical network
By definition, any solution point randomly selected from this Pareto front is superior to all the other points at least in terms of one objective value. Therefore, all these points, which represent toll schemes are possible optimal solutions considering three objectives. The importance of presenting such a Pareto front is, from any solution (toll scheme) to another, trade-offs can be calculated. As a result, the best scheme based on given circumstances can be selected considering the trade-offs. This indicates by using multi-objective optimization it is possible to find solutions with a similar objective value but significantly reducing other negative impacts generated.

For the optimal toll schemes obtained for the hypothetical network, the maximum toll amount charged for each vehicle (per km) found to be A$ 1.41, A$ 1.50, A$ 0.88 and A$ 1.20 for cars, 2 axle, 4 axle and 6 axle trucks respectively. It clearly shows that all toll charges are kept at fairly low rates to optimise the given objectives while making high returns under a majority of the schemes. Out of 145 solutions shown on the Pareto front in Figure 8a, the majority (64%) of the solution schemes achieve an IRR above 5%, which

![Figure 0.8: Pareto-optimal points for real network](image-url)
is above the cost of capital. Similarly, for the optimal toll schemes obtained for the real network (as shown in Figure 8b), the maximum toll amount charged for each vehicle type is found to be A$ 2.48, A$ 1.50, A$ 0.13 and A$ 0.80 for cars, 2 axle, 4 axle and 6 axle trucks respectively. Out of the 200 optimal solutions shown in the Pareto curve in Figure 8b, 31% of the solutions produce an IRR above 5%. This provides many potential solutions (toll schemes) for different stakeholders, such as investors and government authorities, to choose from, which have similar IRRs.

Since EastLink toll charges are fairly low compared to the CityLink toll charges as mentioned above, the CityLink surely be making supernormal profits under the prevailing conditions. In order to evaluate the CityLink toll charges and respective impacts, a typical toll scheme is defined in this study based on the current toll ratio practiced in the Melbourne’s CityLink network as a reference point. From the current toll charge rates in Melbourne’s CityLink, it can be observed that the cars: light commercial vehicles (LCV): heavy commercial vehicles (HCV) toll ratio is approximately 1: 1.6: 3. Even though CityLink’s charge for HCV varies from 0.91 A$/km to 4.61 A$/km (Chen et al., 2018), a representative toll scheme is defined subject to the boundaries considered in this study, given in Table 7.2. In addition, Table 7.2 shows the maximum cost amount (user, environmental and social) found from the Pareto-optimal solutions for each objective, for both case studies. These, extreme solutions (maximum costs) are used to compare with the ‘Typical toll’ scenario.

**Table 0.2:** Details of the maximum solution obtained for each objective on the Pareto front and results for a typical toll scheme

<table>
<thead>
<tr>
<th>Solution</th>
<th>Toll Charge (A$/km)</th>
<th>Objective Value*</th>
<th>Toll Revenue (A$)/(IRR)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Car, 2-axle, 4-axle, 6-axle</td>
<td>User Cost (A$)</td>
<td>Environ. Cost (A$)</td>
</tr>
<tr>
<td>Hypothetical Network</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max. User Costs</td>
<td>1.38, 1.47, 0.00, 0.03</td>
<td>85,741</td>
<td>23,400</td>
</tr>
<tr>
<td>Max. Environ. Costs</td>
<td>0.00, 0.00, 0.00, 0.79</td>
<td>77,365</td>
<td>23,852</td>
</tr>
<tr>
<td>Max. Social Costs</td>
<td>1.41, 1.46, 0.00, 0.00</td>
<td>85,588</td>
<td>23,393</td>
</tr>
<tr>
<td>Typical Toll Scheme</td>
<td>0.85, 1.36, 2.55, 2.55</td>
<td>93,999</td>
<td>24,719</td>
</tr>
<tr>
<td>Real Network</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max. User Costs</td>
<td>0.57, 0.15, 0.02, 0.01</td>
<td><strong>977,744</strong></td>
<td>285,404</td>
</tr>
<tr>
<td>Max. Environ. Costs</td>
<td>2.48, 0.00, 0.01, 0.00</td>
<td>894,558</td>
<td><strong>314,277</strong></td>
</tr>
</tbody>
</table>
From the results presented in Table 7.2, it is evident that the typical toll scheme was designed with an objective to generate a very high IRR and no consideration was given to negative social or environmental impacts generated as a result. For both case studies, the IRR values are above 25%, which is way higher than the cost of capital in Australia. It is also evident from the results presented in Table 7.2 that the typical toll scheme generates much higher externalities compared to the maximum cost generated under optimal solutions. For an example, the maximum user cost generated under the Pareto optimal solutions obtained for the real network is A$977,744 whereas the user costs generated under the typical toll scheme would be A$1,095,394. Therefore, in holistic view, considering all three objectives, the typical toll scheme is producing very high negative impacts on residents, road users (both freight and non-freight) and the general public in terms of user costs, social costs and environmental costs, although it is producing a higher IRR satisfying the investor. In real terms, CityLink is a major transport corridor in Melbourne City which helps to transport a large amount of freight (in terms of weight) every day. Melbourne metropolitan region is identified as having higher freight movements than interstate freight in Australia (Perera et al., 2017). As a result, the negative impacts on residents, other road users and society are quite significant as revealed from the analysis. It is also worth to mentioned that IRR calculation did not consider the traffic demand growth over the years, which is significant in Melbourne due to the expected growth in next few decades (Transport for Victoria, 2018). This means that IRR could be higher than the calculated numbers in this study.

Although in this study externalities are measured in dollar terms, they are not direct expenses incurred by any stakeholder. For example, environmental costs are measures based on negative impacts on human health and social costs are based on opportunity costs, where none of them are direct costs (direct costs related to transportation) to the users or public. As a result, people are still reluctant to accept such indirect charges in order to compensate for direct charges. Therefore, decision makers (e.g. government
authorities) must make a decision on reasonable and acceptable values for coefficients introduced \((\rho, \sigma, \tau, \varphi, \text{ and } \omega)\) for the crash costs, congestion costs, infrastructure costs, emission costs and noise costs under social costs and environmental costs presented in equations (2) and (3)\(^4\). Between any two optimal solution produced here shows a trade-off based on the three objectives considered. Therefore, this information should be presented in the decision-making process where a final desirable scheme can be selected by the decision maker considering all stakeholders inputs (Wu et al., 2016).

### 7.5 Chapter summary

Trucks generate more externalities (environmental and social) than passenger vehicles, especially when trucks divert off freeways. When toll charges increase, sometimes in significant amounts like in Melbourne recently, more trucks tend to avoid toll roads (quality roads) generating more externalities. This adds substantial negative impacts on residents, the environment and society. In fact, determining an optimum toll charge for freight vehicles is a crucial decision to be made by policymakers considering socio-economic aspects. Therefore, the objective of this chapter is to apply the bi-level model developed (mathematical approach) in Chapter 3 to find an optimal toll scheme for multi-class vehicles, including various truck types, considering direct costs and externalities. Further, trade-offs between various objectives of the designed scheme considering given constraints are also found. This NP-hard, non-convex problem with non-linear constraints was solved using NSGA II. The model is applied to a small size hypothetical network and a real network with static demand conditions in order to illustrate differences between common toll schemes. Results are presented for Pareto-optimal solutions where decision makers can chose any solution under the prevailing circumstances.

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\(^4\) For simplicity purpose the environmental cost elements (emission cost and noise cost) are added together assuming equal impact from each element (similarly for the social cost). This approach is also not quite accurate since among the environmental or social costs the significance of impact from individual elements may differ. However, this could be more important at higher level when comparing environmental and social costs, which are two completely different costs.
In summary, this chapter illustrates the method developed to analyze the trade-offs between different stakeholder objectives and what magnitude such impacts can be materialized. This gives decision makers the opportunity to understand the applicability of each policy decision and respective consequences beforehand. As a result, this would help to achieve any objective(s) in a smarter way than causing unnecessary costs (as explained with the example of the typical toll scheme).
Chapter 8

A multi-class Toll-based Approach to Reduce Total Emissions on Roads for City Logistics

8.1 Introduction

Greenhouse gas (GHG) emissions and air pollution are critical problems in many urban areas. Globally 27% GHG emissions were produced by the transport sector (road, air and water) (Creutzig et al., 2011; Zeng et al., 2017), among which road transportation is a major source of air pollution (Caiazzo et al., 2013; Chen and Yang, 2012; Dedoussi and Barrett, 2014; Galgamuwa et al., 2016a). Among road transportation emissions, freight transportation is responsible for the majority of the emissions, even though heavy vehicles only account for a small proportion of the total vehicle population (Iankov, 2016; Leenders et al., 2017; Wang and Rakha, 2017). Among the most widely reported pollutants in vehicular combustion (Brugge et al., 2007; Fuller et al., 2012) PM2.5 and NOx have been found to have a significant negative impact on human health compared to other pollutants from vehicular emissions (Fuller et al., 2012; Malina and Scheffler,
Heavy diesel-powered engines (mostly trucks) are known to produce high levels of PM2.5 and NO\textsubscript{x} compared to petrol fuelled vehicles.

Recent studies have shown that sharp pollutant gradients exist near highways, which can have detrimental effects on the health of people living within these polluted zones (Brugge et al., 2007; Joo et al., 2017; Patton et al., 2014). For example, the pollutions may result in premature births (Mitchell et al., 2005), premature deaths (Caiazzo et al., 2013; Zimmer and Koch, 2017) pulmonary disease and colds and flu among children (Joo et al., 2017). Truck avoidance by freight vehicles and diversion to local roads have caused complains by local residents demanding for ‘Truck Bans’ in Melbourne (MTAG, 2016). Therefore, a sustainable solution to reduce overall emissions as well as to stop trucks from avoiding tolls by taking local roads is needed in the long run to safeguard human health and the environment.

In order to reduce emissions from road transportation and their potential negative impact on human health and the environment, several measures have been implemented by authorities in the road transport sector worldwide. These measures can be categorized as land-use policies, transport demand management measures, fleet management measures, infrastructure investment measures, fuel pricing policy reformation and encouragement to use alternative fuel technologies. In addition, researchers have suggested emission-based optimum routing, eco-friendly driving and toll optimization techniques to reduce emissions from road transport (Ahn and Rakha, 2013; Jabir et al., 2017; Wang et al., 2017).

However, these initiatives often have drawbacks when applied to real-world transport systems. First, these initiatives usually focus on a cordon area with the given objective and what happens beyond the area being completely neglected (Prud’homme and Bocarejo, 2005; Rotaris et al., 2010). Secondly, some of these measures, such as establishing environmentally friendly transportation systems in the long run, often cost a substantial amount of money and time to implement (Ahn and Rakha, 2013; Browne et al., 2011). Thirdly, most of these studies are limited to passenger transport and freight transportation is often neglected (Sugawara and Niemeier, 2002; Zeng et al., 2017; Zhao 2015; Zhu et al., 2002).
et al., 2016). There has been limited research on practical, less financial oriented solutions concerning freight movement in City Logistics.

This study proposes an optimization-based approach to optimize toll charging schemes to reduce total emissions and air pollution on roads from both passenger and freight transportation. As part of this study, the following questions are investigated: 1) how common toll charging schemes affect overall emissions from transport networks, and 2) how toll charging schemes can be used to minimize emissions (represented by emission costs) in city logistics while generating reasonable revenue for investors.

The rest of this paper is structured as follows. Section 8.2 briefly reviews past related work. Section 8.3 introduces methods developed to minimize emission costs, using the bi-level model. Results are presented and analyzed in Section 8.4 and Section 8.5 presents a summary of this study.

8.2 Background

8.2.1 Emission estimation models

Past studies have used CO\textsubscript{2}/CO emission models to estimate emissions (Benedek and Rilett, 1998; Chen and Yang, 2012; Nagurney, 2000; Nagurney and Dong, 2002; Sugawara and Niemeier, 2002; Yin and Lawphongpanich, 2006; Zhang et al., 2010), which only cover the negative impacts on the environment (Velázquez-Martínez et al., 2016; Wen and Eglese, 2016). However, PM\textsubscript{2.5} and NO\textsubscript{x} components within traffic emissions which have a significant negative impact on human health have often been neglected (Fuller et al., 2012; Malina and Scheffler, 2015; Zhu et al., 2002). Although recent studies have developed drive cycle (DC) models that consider microscopic emission from vehicles, which can be used to estimate emissions (Coelho et al., 2009; Frey et al., 2008, 2003; U. Galgamuwa et al., 2015; Gamalath et al., 2012; Ho et al., 2014; Huertas et al., 2017; Kumar Pathak et al., 2016; Romero et al., 2017; Wang and Rakha, 2017), such models have not been used in emission studies due to their high cost (Galgamuwa et al., 2016b) and complexity (Galgamuwa et al., 2015). Therefore, it is important to consider at least at a macro level, emission models with all major
components which may have significant effects on the environment as well as human health when looking at emission reduction strategies. Details of the existing emission models and how they have been used in this study are given in Chapter 3, Chapter 4 and in section 8.3.

8.2.2 Bi-level approach, multi-class traffic, and network effect

A bi-level framework has been successfully used in the past to investigate reducing emissions. Zhao et al. (2016) used a bi-level model framework to achieve an emission reduction target using a differentiated toll charging scheme across various travel modes. Wen and Eglese (2016) studied how CO$_2$ can be minimized in a two-link network using a bi-level, dynamic model. An aggregated CO$_2$ emission model for light goods vehicles was developed by Zeng et al. (2017) and a trip-assignment model was developed by Sugawara and Niemeier (2002) to systematically compute emission-optimized traffic flows considering light trucks. However, in the majority of these studies, only passenger vehicles or light trucks were considered, while large freight vehicles have been ignored (Jabir et al., 2017; Sugawara and Niemeier, 2002; Wen and Eglese, 2016; Zeng et al., 2017; Zhao et al., 2016). Since freight vehicles are known to produce more emissions compared to light goods vehicles (Iankov, 2016; Leenders et al., 2017; Wang and Rakha, 2017), the main contributors (trucks) are missing in previous emission studies.

8.2.3 Freight vehicles routing optimization

Freight routing problems have been examined in the past focusing on emission controls considering both freight vehicles and routes (Ahn and Rakha, 2013; Jabir et al., 2017; Wang et al., 2017). However, most of these studies have looked at individual optimization processes in a sequence of origins and destinations for freight deliveries, while the effect from mixed vehicles and the network was not considered (Jabir et al., 2017). Some advanced technologies have also been used to examine eco-routing strategies (e.g. centralized traffic management system) (Ahn and Rakha, 2013; Zeng et al., 2017). However, typically these technologies are limited to theoretical studies without application to real-world networks. This is mainly due to the fact that energy or
environmental impacts are not usually considered by users in route choice decision making (Ahn and Rakha, 2008). In addition, high infrastructure and operational costs were found to be another prevailing reason limiting eco-friendly routing (e.g. approaches developed to minimize freight emissions considering variations in land use and road conditions) (Velázquez-Martínez et al., 2016). Therefore, user acceptance, infrastructure costs and operating costs need to be considered when providing an effective solution to emissions control considering freight routing.

8.2.4 Roadside emissions

The impact on health from vehicle emissions is related to both the strength of the emission source and how close they live near the highways (Brugge et al., 2007; Fuller et al., 2012; Patton et al., 2014). The strength of the emissions measured in terms of density has a major impact on humans mortality and morbidity (Zhu et al., 2002). The recent past studies have discovered that sharp pollutant gradients exist near highways (Brugge et al., 2007) and spatial distribution of such pollutants has been studied by (Fuller et al., 2012; Patton et al., 2014). These studies found that people living or spending substantial time within 200m of highways are exposed to highly polluted air (Brugge et al., 2007), and transition zone upto 650 m exist from major highways, where emissions have an impact on human health (Patton et al., 2014). In addition, this transition zone is extended to 1 km radius when a crash occurs on a freeway (Joo et al., 2017). A previous study shows that approximately 11% of US households are located within 100m of 4-lane highways (Brugge et al., 2007) and similar conditions can be assumed in urban areas in other developed countries. Therefore, it is important to consider the distance to households from emissions sources (roads) apart from the strength of the emissions.

In Melbourne, Australia, the impact from roadside emissions can be proven by the rate of children’s asthma and related respiratory admissions to hospital, which is 171% of the national average reported from one of the affected areas in Melbourne (MTAG, 2016). These social complaints have become very serious over time and authorities have taken actions such as truck bans on certain links and road curfews for trucks during school times to control such conditions.
8.3 Methodology

8.3.1 Problem formulation

The same bi-level model explained in Chapter 3 was used here with minor changes. In this Chapter, the upper level objective has changed to minimize emissions on roads without introducing a complex charging system. Thus, toll charges for different types of vehicles on toll roads are selected as the decision variables to shape the behavior of road users. Since toll charges are the only revenue source for the investors (toll company) and they need to make a decent return on their investment, toll revenue is considered as one of the constraints.

In this bi-level model, the upper-level problem is formulated as:

\[
\min Z = \sum_{a} \sum_{m} E_{a}^{m} x_{a}^{m} \quad (8.1)
\]

Subject to

\[
TR = \sum_{a} \sum_{m} T_{a}^{m} x_{a}^{m} \geq TR_{L} \quad (8.2)
\]

Where,

- \( Z \) : Total emission cost from the network (A$)
- \( a \) : Road link \( a \in A \cup \bar{A} \), where \( A \) denotes set of un-toll links and \( \bar{A} \) denotes toll links
- \( m \) : Vehicle type, \( m \in M \), where \( M \) denotes set of multi-class vehicles
- \( E_{a}^{m} \) : Emission cost for given vehicle type, on a given link \( a \), \( a \in A \cup \bar{A} \), \( m \in M \) (\$/km)
- \( x_{a}^{m} \) : Traffic flow on the link \( a \) w.r.t vehicle type, \( a \in A \cup \bar{A} \), \( m \in M \) (veh/hr)
- \( T_{a}^{m} \) : Toll charge for each vehicle type for the given link \( a \), \( a \in \bar{A} \), \( m \in M \) (A$/km)
- \( TR \) : Toll Revenue (A$)
- \( TR_{L} \) : The lower limit of the Toll Revenue accepted by the Investor (A$)
Equation (8.1) is the objective function of the upper-level, which minimizes the total emission costs of transportation. Equation (8.2) introduces the main constraint for the upper-level objective function, which is the condition that the revenue generated from toll charges must be above a minimum threshold level that is acceptable for investors.

There is no change to the lower level of the bi-level model and the equations are not presented here. Equations (8.3) and (8.4) presented below are the additional constraints associated with the objective function (8.1). Equation (8.3) denotes the non-negativity of traffic flows whereas equation (8.4) denotes the boundaries defined for individual toll charges.

Additional constraints considered include:

\[ x_{a}^{m} \geq 0, \quad \forall \ a \in A \cup \bar{A}, m \in M \]  \hspace{1cm} (8.3)

\[ 2.55 \geq T_{a}^{m} \geq 0, \quad \forall \ a \in A \cup \bar{A}, m \in M \]  \hspace{1cm} (8.4)

### 8.3.2 Genetic algorithm optimisation

Genetic algorithms (GAs) are a heuristic search mechanism based on the ideas of natural selection and genetics (Goldberg and Richardson, 1987; Weile and Michielssen, 1997). GAs have been used to solve many complex engineering problems, such as heat exchanger network synthesis optimization in industrial plants (Ravagnani et al., 2005), the unit commitment problem in power systems (Kazarlis et al., 1996) and the integrated inventory-distribution problem in supply-chain management (Abdelmaguid and Dessouky, 2006) and optimisation problems in the transport sector (Ahn and Ramakrishna, 2002; Cheng et al., 2018; Fan and Machemehl, 2006; Shepherd and Sumalee, 2004; Teklu et al., 2007; Wren and Wren, 1995).

The basic idea of a GA is to represent potential solutions of a problem (i.e. a combination of toll charges for different vehicle types in this study) as a finite length array called a ‘chromosome’ and the objective function and constraints associated with each solution are calculated using a simulation model. The collection of these chromosomes is called a population. A chromosome can be in the form of binary, integer or real numbers based
on the problem under consideration and a user’s preference. GAs use three genetic operators, including selection, cross-over, and mutation, to search for better solutions in each generation/iteration. The search behavior of GAs is controlled by parameters related to these operators.

Chromosomes with a high fitness level (i.e. better objective function values and meeting the constraint requirements) have a higher probability of survival during the selection process. The surviving chromosomes then reproduce and form chromosomes for the next generation through ‘crossover’ and ‘mutation’ processes. The population size used, a number of generations carried out, cross-over and mutation rates are critical for finding better solutions. For example, large populations and generations are quite useful in terms of finding better solutions but consume more computing power. Therefore, for a given problem a suitable population size and number of generations needs to be determined considering the complexity of the problem. In this study, a sensitivity analysis was conducted to find a combination of population size, a number of generations, cross-over and mutation rates to make sure near-optimal solutions are found. Since Gas are a stochastic method, multiple random seeds were used to minimize the impact of the initial starting population on the optimization results.

### 8.3.3 Toll charging scenarios

Four different toll charging scenarios with fixed traffic demand conditions were used in this study to investigate user response to tolls and the resulting emissions, operation costs, toll revenue and total travel time. These scenarios are summarised in Table 8.1. The first two scenarios are based on two popular toll charging methods in the world and the third scenario is based on a present toll scheme in Melbourne, Australia. The final scenario is an extension of the first scenario which has been introduced to elaborate better solutions. Details of the four toll charging scenarios are as follows.

The first scenario considered is a distance-based toll charge, where the toll charge rate in A$/km for a particular vehicle type is fixed for all links in the network. However, under this scenario (‘Fixed Toll’), different vehicles may be charged a different rate and there is no specific toll ratio applied. The distance-based toll charging scenario is one of the
popular and common methods used around the world (Gammelgaard et al., 2006; Jou et al., 2012; O’Mahony et al., 2000), due to its simplicity. Under this ‘Fixed Toll’ scenario various objectives are optimized considering three major stakeholder objectives identified in the problem formulation section above. In addition, for completeness of the scenario and for comparison purposes, two other extreme toll charging schemes, zero tolls and highest toll, were also simulated for the networks under scenario 1.

The second scenario is the Gross Vehicle Mass or GVM-based toll charging scenario. This scenario tries to capture the pavement damage caused by each vehicle as a function of the GVM of the vehicle. This is another popular charging method practiced in some countries such as Germany (Link, 2008; McKinnon, 2006a, 2006b). In this study, GVM Values used for cars, 2 axle trucks, 4 axle trucks, and 6 axle trucks are 1.5, 15, 27.5 and 42.5 tonnes, respectively (Perera et al., 2018). In simple terms, the ratio of tolls charged for cars, 2 axle trucks, 4 axle trucks, and 6 axle trucks are 1:10:18:28. In this study, the toll charge for cars is considered as the decision variable since toll charges for other vehicle classes are automatically defined based on the ratio above. The maximum toll charge considered for any vehicle type is A$2.55, hence the upper toll level for the 6-axle vehicle was fixed at A$ 2.55. With such limitation, only a small number of discrete toll schemes are available under this scenario and thus no optimization algorithm was applied. Instead, all the possible outcomes were evaluated.

The third scenario is a ‘Typical Toll’ scenario, which has only one toll scheme based on the present toll charging level in CityLink, Melbourne. CityLink freeway in Melbourne has variable toll charges for various sections for any type of vehicle, but the ratio between multi-classes are kept constant. The same toll ratio, which is 1: 1.6: 3 for cars: light commercial vehicle (LCV): heavy commercial vehicle (HCV) is used in this study assigning the maximum toll charge for HCV (A$ 2.55).

Since toll roads developed under public-private partnerships (PPP) are often equipped with an electronic toll collection system (Holguín-Veras et al., 2006; Lay and Daley, 2002) (e.g. CityLink and EastLink in Melbourne), it is practical to charge variable tolls based on vehicle type and different road sections with less administrative difficulties. This variable charging mechanism is practiced on both CityLink and EastLink roads, charging various
amounts for different sections of the road. More information on toll charging practice in the CityLink and the EastLink roads can be found in Perera et al. (2016). Therefore, a more flexible toll charging scenario defined as “Link specific distance based multi-class toll charge” is considered in this study, to move beyond the ‘Fixed Toll’ charging scenario. This flexible toll charging scenario is similar to the ‘Fixed Toll’ scenario except that in the ‘Fixed Toll’ scenario the same toll scheme is applied to all toll links in the network, whereas in ‘Link Toll’ scenario the toll scheme may vary from link to link within the network. This ‘Link Toll’ is used to explore whether there are any better solutions beyond the standard schemes discussed above.

Under each scenario, toll charging schemes were optimized based on different objectives, as listed in Table 8.1.

**Table 0.1:** Different toll charging scenarios and the objectives optimized under each scenario

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Referred as</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1.</strong> Fixed distance based multi-class toll charge (fixed for all toll links)</td>
<td>Fixed Toll</td>
</tr>
<tr>
<td>Min. Emissions</td>
<td></td>
</tr>
<tr>
<td>Max. Revenue</td>
<td></td>
</tr>
<tr>
<td>Min. Operation Cost</td>
<td></td>
</tr>
<tr>
<td>Zero Toll</td>
<td></td>
</tr>
<tr>
<td>Highest Toll</td>
<td></td>
</tr>
<tr>
<td><strong>2.</strong> Gross-Vehicle-Mass (GVM) Based toll</td>
<td>GVM Toll</td>
</tr>
<tr>
<td>Min. Emissions</td>
<td></td>
</tr>
<tr>
<td>Max. Revenue</td>
<td></td>
</tr>
<tr>
<td><strong>3.</strong> Typical scenario (representing Melbourne CityLink)</td>
<td>Typical Toll</td>
</tr>
<tr>
<td>Typical Toll</td>
<td></td>
</tr>
<tr>
<td><strong>4.</strong> Link specific distance based multi-class toll charge</td>
<td>Link Toll</td>
</tr>
<tr>
<td>Min. Emissions</td>
<td></td>
</tr>
<tr>
<td>Max. Revenue</td>
<td></td>
</tr>
</tbody>
</table>

8.4 Results and discussion

A Genetic Algorithm (GA) was used to find the optimum toll values for some objectives under each scenario listed in Table 8.1. Integer coding was used in the GA optimization,
which leads to a chromosome with a length of 4 bits for the first three scenarios and a larger chromosome with 24 bits for the hypothetical network and 268 bits for the real-world network. Sensitivity analysis was conducted to determine the best values for parameters, which are 200 population size, 100 generations, cross-over rate of 0.8 and a mutation rate of 0.05. Ten random seeds were used to find near-optimal solutions for each scenario (except for ‘Typical Toll’ scenarios, where a pre-defined toll charging scheme is used).

8.4.1 Results from the hypothetical network

The results obtained from the hypothetical network for different toll charging scenarios are presented in Table 8.2 below. The numbers given in total (OC, EC and TT) are based on the entire network, but not limited to freeway or other roads. It is important to look at totals, irrespective of road type based numbers (for freeways and other roads separately) since the objective is to look at the overall output, which is not limited to any road segment. A pair wise comparison carried out between min. emissions toll scheme and the typical toll scheme is presented in Table 8.3. The results for the ‘Link Toll’ scenario are presented in Table 8.4.

Table 0.2: Decision variables and objective function values of different solutions under different scenarios

<table>
<thead>
<tr>
<th>Toll Charging Schemes Under Different Toll Scenarios</th>
<th>Toll Revenue (A$)</th>
<th>Toll Charges for Different Vehicles <a href="A$/km">cars, 2 axles, 4 axles and 6 axles</a></th>
<th>Total OC (A$)</th>
<th>Total EC (A$)</th>
<th>Total TT (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fixed Toll Scenario</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Min. Emissions</td>
<td>5,144</td>
<td>0.63, 0.07, 0.37, 0.02</td>
<td>76,081</td>
<td>18,274</td>
<td>97,737</td>
</tr>
<tr>
<td>Max. Revenue</td>
<td>17,179</td>
<td>2.39, 1.36, 2.53, 1.61</td>
<td>79,899</td>
<td>19,328</td>
<td>110,064</td>
</tr>
<tr>
<td>Min. Operation Cost</td>
<td>7,790</td>
<td>0.96, 0.65, 0.01, 0.39</td>
<td>76,049</td>
<td>18,305</td>
<td>97,837</td>
</tr>
<tr>
<td>Zero Toll</td>
<td>0.00</td>
<td>0.00, 0.00, 0.00, 0.00</td>
<td>76,361</td>
<td>18,325</td>
<td>98,447</td>
</tr>
<tr>
<td>Highest Toll</td>
<td>13,389</td>
<td>2.55, 2.55, 2.55, 2.55</td>
<td>88,160</td>
<td>20,610</td>
<td>134,142</td>
</tr>
<tr>
<td><strong>GVM Toll Scenario</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Min. Emissions</td>
<td>0.00</td>
<td>0.00, 0.00, 0.00, 0.00</td>
<td>76,361</td>
<td>18,325</td>
<td>98,447</td>
</tr>
<tr>
<td>Max. Revenue</td>
<td>7,115</td>
<td>0.077, 0.77, 1.386, 2.156</td>
<td>77,709</td>
<td>18,762</td>
<td>101,036</td>
</tr>
<tr>
<td>** Typical Toll Scenario**</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Typical Toll</td>
<td>12,167</td>
<td>0.85, 1.36, 2.55, 2.55</td>
<td>81,832</td>
<td>19,746</td>
<td>107,325</td>
</tr>
</tbody>
</table>
8.4.1.1 Discussion of results from the ‘Fixed Toll’ scenario

Under scenario 1, the ‘Fixed Toll’ scenario presented in Table 8.2, five toll schemes are presented out of which three schemes are optimizing different objectives while the remaining two corresponds to two extreme toll conditions. In this sub-section comparisons are made between results obtained for different ‘Fixed Toll’ schemes in order to evaluate the acceptance of the minimum emission scheme proposed in this study.

The results show that the optimal solutions obtained by minimizing total emissions are similar to that obtained by minimizing total operating costs under the ‘Fixed Toll’ scenario. Both solutions have a total operating cost of around A$76,000, an emissions cost of around A$18,000 and a total travel time of around 97,000 minutes. However, the resulting toll revenues are slightly different: the minimum emission solution generated total revenue of A$ 5,144, whereas the minimum operation cost solution generated revenue of two-and-a-half thousand dollars higher. Both solutions have high tolls for cars compared to commercial vehicles but at a different magnitude.

In contrast, the revenue maximization solution leads to higher toll revenue, but the resulting toll charges are very high for all vehicle categories compared to the two other solutions discussed above. Further, all negative impacts (total operation costs, total emission costs, and total travel times) considered in this study are higher for max. revenue solution than the previous 2 solutions (min. emissions and min. operation cost) discussed above. The emission minimizing solution and operation cost minimizing solutions generate about 30% and 46% toll revenues compared to maximum revenue solution respectively, but with significantly lower negative impacts. Therefore, this study demonstrates that revenue requirements need to be considered together with the negative impacts they produce before blindly choosing a maximum revenue scheme. However, the toll revenue threshold required to protect the investor is not yet known and thus more investigation is required in order to find the best toll scheme. As clearly shown in the results, high toll charges, especially for heavy vehicles, compel heavy vehicles to avoid quality roads (toll roads) producing more externalities while achieving maximum toll revenue.
One may argue that the zero-toll scheme might generate lower emission levels irrespective of the revenue generated from the network point of view. However, this is incorrect based on the results obtained in this study, which show that zero toll charges led to emissions cost levels higher than that from the minimum emissions solution as well as the minimum operation cost solution. The zero-toll scheme also generates high negative impacts on operation cost as well as total travel time compared to both minimum emissions and minimum operation cost solutions. The worst among such negative impacts is the increase in total operating costs, which is least expected by road users from a zero-toll scheme. Overall, this toll scheme would not be accepted by any of the stakeholders because all cost elements are comparatively high in this scheme compared any of the other schemes discussed above. The underlying reason for such inefficiency in zero toll scheme is due to no access control to quality roads (toll roads) by vehicle type and thus running out of capacity for vehicles (HV) which needs to use toll roads to reduce externalities.

In contrast to the zero-toll scheme, this study also looked at the impacts caused by charging the highest toll from all vehicle types, described as the highest toll scheme above. Even though the rational expectation from this scheme is to generate the highest toll revenue, it generated only 78% of the revenue generated under the maximum revenue solution (under ‘Fixed Toll’ scenario). In addition, total operation costs, total emissions costs, and total travel times (negative impacts) are higher an increase of 10%, 7% and 22% respectively, compared to the maximum revenue solution. Again, the underlying reason for such an outcome of this scheme is opposite to the zero-toll scheme. The high toll charges lead to all vehicle types to avoid toll roads, resulting in major demand increase in the links on the rest of the network. This high demand in the rest of the links in the network leads to the production of higher emission costs and other negative impacts.

From this analysis, it is clear that there are some ‘Fixed Toll’ based scenarios that are very inefficient (in terms of three stakeholder objectives) and should never be considered for implementation. At the same time, it was proven that the minimum
emissions toll scheme produced a reasonable outcome which can be accepted by all three stakeholders.

**8.4.1.2 Discussion of results obtained under the ‘GVM Toll’ scenario**

Figures 8.1 and 8.2 present the results obtained from the ‘GVM Toll’ scenario. In Figure 5, when car toll charges are above A$ 0.05, emission costs start increasing rapidly but a reduction in the rate of increasing toll revenue can be observed. From Figure 6, it can be observed that toll revenue up to A$ 5,750 can be earned without causing much addition environment costs. There is a general belief that toll charges and toll revenue have a monotonic relationship, but it was found to be different in this study at upper extreme levels. Figures 5 and 6 together show that toll revenue would not increase as toll charges increase and there’s an optimum revenue amount (A$ 7,115) that can be achieved. In addition, it shows that there are different toll charges which can achieve the same revenue with higher or lower emission costs and thus planners must be very careful when choosing high toll prices expecting to earn more revenue because they may select the wrong price which may generate greater environmental impacts needlessly.
Figure 0.1: Car toll charge vs emission cost and toll revenue

However, toll schemes considered under ‘GVM Toll’ scenario do not provide any better solutions than toll schemes considered under ‘Fixed Toll’ scenario in terms of their intended objective and the respective impacts are concerned.

8.4.1.3 Pair wise comparison of results obtained for the ‘Fixed Toll’ scenario and ‘Typical Toll’ scenario

This sub-section will compare one of the existing toll schemes in Melbourne (‘Typical Toll’) with the minimum emissions toll scheme proposed under the ‘Fixed Toll’ scenario. Table 8.3 presents the pair wise comparison made between the typical toll scheme (‘Typical Toll’ scenario) and min. emissions toll scheme (‘Fixed Toll’ scenario).

Table 0.3: Pair wise comparison of the typical toll scheme (under the ‘Typical Toll’ scenario) and minimum emission toll scheme (under the ‘Fixed Toll’ scenario)
The above results show that even though the minimum emissions toll scheme generates less toll revenue compared to the typical toll scheme, there is a significant improvement in relation to emission costs, operating costs and the total travel time. For example, there is a 7% reduction in total operation costs and a 7.5% reduction in total emission costs in the minimum emissions scheme compared to the typical toll scheme. Finally, the total cost saving, which is about A$7,223, is greater than the difference in toll revenue generated (A$7,149). In addition to the monetary terms, an 8.9% saving from the total travel time provides more strength in the minimum emission toll scheme compared to the typical toll. Therefore, it can be concluded that the present toll charges are not efficient to obtain maximum benefits considering both upper level and lower level stakeholder objectives, necessitating a further investigation into more sensible ways of setting toll charges under a multi-stakeholder multi-objective framework.

### 8.4.1.4 Discussion of results obtained under the 'Link Toll' scenario

Since the ‘Link Toll’ scenario is a relaxed version of the ‘Fixed Toll’ scenario and intended to produce better results with respect to the given objective. Only two major objectives are considered here since it was found that the useroptimized solution is similar to the minimum emissions solution. The results from the ‘Link Toll’ scenario is presented in Tables 8.4. The link wise multi-class toll schemes obtained under min. emissions and max. revenue objectives are given in Appendix 8a.

<table>
<thead>
<tr>
<th></th>
<th>Typical Toll</th>
<th>Min. Emissions</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Toll Revenue (A$)</strong></td>
<td>12,167</td>
<td>5,018</td>
<td>(7,149) (58.8%)</td>
</tr>
<tr>
<td><strong>Operation Cost (A$)</strong></td>
<td>81,832</td>
<td>76,081</td>
<td>5,751 (7%)</td>
</tr>
<tr>
<td><strong>Emissions Cost (A$)</strong></td>
<td>19,746</td>
<td>18,274</td>
<td>1,472 (7.5%)</td>
</tr>
<tr>
<td><strong>Total Cost (A$)</strong></td>
<td>101,578</td>
<td>94,355</td>
<td>7,223 (7.1%)</td>
</tr>
<tr>
<td><strong>Total Travel Time (min)</strong></td>
<td>107,325</td>
<td>97,737</td>
<td>9,588 (8.9%)</td>
</tr>
</tbody>
</table>

Table 0.4: Optimal toll charging schemes under the link toll scenario
The optimized solutions under the ‘Link Toll’ scenario considering two objectives; minimizing emissions and maximizing revenue resulted in significant improvements in both objectives compared to the respective solutions obtained under the ‘Fixed Toll’ scenario. The total emissions cost for the network (in minimum emissions solution under ‘Link Toll’ scenario) was reduced by A$ 154 (1%) and the revenue was increased substantially by A$ 2,098 (41%) compared to the ‘Fixed Toll’ minimum emission toll scheme proposed above. These improvements in the minimum emissions objective were achieved at the expense of travel time and total operating cost. The solution results in a net loss of 1,188 minutes (1.2%) in total travel time and A$ 113 (less than 1%) increase in the total operating costs. Similarly, the total emission cost for the network (in maximum revenue solution under ‘Link Toll’ scenario) was reduced by A$ 151 (1%) and the revenue was increased by A$ 2031 (12%) compared to the ‘Fixed Toll’ maximum revenue toll scheme presented above. In addition, there was saving from the total travel time, which is about 3,041 minutes (3%) but an increase in operation cost of A$ 268 (less than 1%).

When the overall solutions for ‘Fixed Toll’ scenario (Table 8.2) is compared with the overall solutions obtained for ‘Link Toll’ scenario (Table 8.4), for two objectives, it is very clear from the results that for both objectives the ‘Link Toll’ scenario provides better solutions than ‘Fixed Toll’ scenario. Therefore, we propose a ‘Link Toll’ scenario as a better method to reduce network-wide emissions while generating better revenue.

### 8.4.2 Results from the large real-world network

The proposed bi-level model was applied to the real network introduced above and the results obtained for various toll scenarios are presented in Table 8.5.
Emissions reduction

Table 0.5: Decision variables and objective function values of different solutions under different scenarios

<table>
<thead>
<tr>
<th>Toll Charging Schemes Under Different Toll Scenarios</th>
<th>Toll Revenue (A$)</th>
<th>Toll Charges for Different Vehicles [cars, 2 axles, 4 axles and 6 axles] (A$/km)</th>
<th>Total OC (A$)</th>
<th>Total EC (A$)</th>
<th>Total TT (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixed Toll Scenario</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Min. Emissions</td>
<td>72,348</td>
<td>0.40, 0.11, 0.01, 0.01</td>
<td>876,681</td>
<td>179,720</td>
<td>908,083</td>
</tr>
<tr>
<td>Max. Revenue</td>
<td><strong>229,953</strong></td>
<td>0.85, 0.81, 0.74, 0.68</td>
<td>889,890</td>
<td>195,352</td>
<td>894,106</td>
</tr>
<tr>
<td>Min. Operation Cost</td>
<td>185,222</td>
<td>0.92, 0.86, 0.27, 0.18</td>
<td><strong>875,557</strong></td>
<td>187,389</td>
<td>893,380</td>
</tr>
<tr>
<td>Zero Toll</td>
<td>0.00</td>
<td><strong>0.00, 0.00, 0.00, 0.00, 0.00</strong></td>
<td>879,372</td>
<td>181,242</td>
<td>914,489</td>
</tr>
<tr>
<td>Highest Toll</td>
<td>16,307</td>
<td><strong>2.55, 2.55, 2.55, 2.55</strong></td>
<td>975,140</td>
<td>209,757</td>
<td>1,165,3</td>
</tr>
<tr>
<td>GVM Toll Scenario</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Min. Emissions</td>
<td>0.00</td>
<td><strong>0.00, 0.00, 0.00, 0.00, 0.00</strong></td>
<td>879,372</td>
<td><strong>181,242</strong></td>
<td>914,489</td>
</tr>
<tr>
<td>Max. Revenue</td>
<td><strong>73,442</strong></td>
<td>0.084,0.84, 1.512,</td>
<td>907,351</td>
<td>203,152</td>
<td>901,260</td>
</tr>
<tr>
<td>Typical Toll Scenario</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Typical toll</td>
<td><strong>176,456</strong></td>
<td>0.85, 1.36, 2.55, 2.55</td>
<td>919,123</td>
<td>205,242</td>
<td>916,999</td>
</tr>
</tbody>
</table>

8.4.2.1 Discussion of results from the ‘Fixed Toll’ scenario

Under the ‘Fixed Toll’ scenario, the optimal solution obtained by minimizing total emissions and the optimal solution obtained by minimizing the total operation cost shows similar outcomes with respect to total operation cost and total emissions cost. However, it is important to note that these two optimal solutions do not have similar toll revenues, which was the case with the hypothetical network. The results from a large network have amplified the magnitude of the results obtained from the hypothetical network.

The solution obtained under the highest toll objective (under ‘Fixed Toll’ scenario) was not able to produce any reasonable toll revenue compared to any other toll scheme presented under any of the scenarios discussed in this study, except for the zero-toll scheme. Therefore, it can be concluded that higher toll charges would not necessarily generate higher toll revenues. In comparison, it is important to note that the toll revenue generated under the optimal solution for the maximum revenue objective is high compared to any other cases presented in Table 5. The maximum revenue solution
also produced high negative impacts (emissions and operation cost) compared to both minimum emissions or minimum operation cost results.

Similar to the hypothetical network, results obtained for a zero toll scheme in a large network do not provide any better solution from any stakeholder viewpoint. Therefore, zero toll scheme is not a sustainable solution for city logistics and this proves that quality roads should have some control over multi-class vehicle access (multi-class toll is one of the ways of doing it) to maintain network efficiency.

Again, it can be concluded that the minimum emissions toll scheme produced a reasonable outcome in a large network which can be accepted by all three stakeholders.

8.4.2.2 Discussion of results obtained under the ‘GVM Toll’ scenario

The results obtained for the GVM toll scenario from the large real-world network is presented in Figures 8.3 and 8.4. Again the results are similar to the hypothetical network except for the emission cost trend with respect to lower toll charges. In the large network, the emission cost tends to increase as GVM based toll prices increase, which is relatively different from the outcome observed under the hypothetical network. Taking a closer look at the large network traffic volumes and respective capacities revealed that most of the roads (highways) around the freeway under consideration are not congested during the peak times, creating many options for vehicles on the toll road to leave and find an alternate route which maximizes their individual benefit. This was not the case in the hypothetical network where most of the roads have reached their capacity and small differences (bias value with respect to small toll charges) would not make a huge change in the network traffic flows.

The toll revenue shows the same pattern as with the hypothetical network and beyond a certain limit, the toll revenue trend line is reversed. Car toll charges above A$0.03 would make very little marginal revenue at the expense of high marginal emission costs and thus toll operators need to be careful not getting into this red zone. However, both CityLink and EastLink toll schemes appear to be similar in terms of the toll charge ratio used in the GVM scenario. As a result, the current toll charging level used for the CityLink
and EastLink schemes can potentially lead to solutions having significantly higher emission costs.

Figure 0.3: Car toll charge vs emission cost and toll revenue
8.4.2.3 Pair wise comparison of results obtained for the ‘Fixed Toll’ scenario and ‘Typical Toll’ scenario

When the solution obtained under the ‘Typical Toll’ scenario is compared with the minimum emissions solution obtained under ‘Fixed Toll’ scenario, the minimum emissions solution toll scheme was able to generate 12% fewer emissions. In addition, there are other impacts that need to consider such as operation cost reduction and total travel time reductions along with the emissions and revenue.

Further, the ‘Typical Toll’ has only generated about 77% of the maximum revenue that can be generated under the ‘Fixed Toll’ scenario, with a substantial increase in impacts. This indicates the Typical toll scheme is inefficient considering both the investors’ and the residents’ interests. As a result, an analysis considering outcomes beyond the traditional economic objective is required prior to set up a toll scheme on urban toll roads evaluation to promote sustainable city logistics.
8.4.2.4 Discussion of results obtained under the ‘Link Toll’ scenario

Table 8.6 presents the results obtained from the ‘LinkToll’ scenario applied to the large real-world network.

Table 0.6: Optimal toll charging schemes under the link toll scenario for the real network

<table>
<thead>
<tr>
<th>Objective</th>
<th>Toll Revenue (A$)</th>
<th>Total Operation Cost (A$)</th>
<th>Total Emissions Cost (A$)</th>
<th>Total Travel Time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min. Emissions</td>
<td>77,232</td>
<td>875,574</td>
<td>179,058</td>
<td>909,395</td>
</tr>
<tr>
<td>Max. Revenue</td>
<td><strong>238,683</strong></td>
<td>890,649</td>
<td>195,595</td>
<td>894,206</td>
</tr>
</tbody>
</table>

The total emissions cost for the network (in minimum emissions solution under the ‘Link Toll’ scenario) was reduced by A$ 662 (less than 1%) and the revenue was increased by A$ 4,884 (6.8%) compared to the ‘Fixed Toll’ minimum emission toll scheme proposed above. These improvements in the minimum emissions objective were achieved at the expense of travel time, but there is a benefit from the total operating cost. The solution results in a net loss of 1,312 minutes (less than 1%) in total travel time and A$ 1,107 (less than 1%) reduction in the total operating costs.

The toll revenue from the large network under the ‘Link Toll’ scenario was increased by A$ 8,730 (3.8%) compared to the ‘Fixed Toll’ maximum revenue solution. However, this increase was achieved at the expense of total emissions cost (A$ 243), total operation cost (A$ 759) and total travel time (100 min).

Overall, the ‘Link Toll’ scenario provided positive benefit compared to the ‘Fixed Toll’ scenario, under the given objective. However, these solutions are not entirely better (considering all aspects) than the solutions obtained under the ‘Fixed Toll’ scenario. Therefore, planners may need to consider the trade-offs before applying such toll schemes.
8.4.3 Common findings and discussion

The fuel cost (fuel consumption into fuel price) found to be the main contributory factor for operating cost of any freight vehicle type and the same fuel consumption is a major factor determining total emissions as well. As a result, it can be observed that in both case studies, the solutions with the minimum operating cost have similar values in minimum emissions solution. Either zero toll or highest toll schemes in both case studies did not generate any promising results with respect to any stakeholder objective. Similar results were obtained for ‘GVM Toll’ in both case studies where none of the solutions generated a better result than the respective ‘Fixed Toll’ solution. For both case studies, the typical toll schemes are inefficient in revenue generation or emission reduction and the minimum emission solution under ‘Fixed Toll’ scenario produced significant emissions reductions.

Due to the flexibility given in ‘Link Toll’ charges it was expected to have a more favorable outcome from ‘Link Toll’ scenarios compared to the ‘Fixed Toll’ scenarios considered. Thus, the ‘Link Toll’ scenarios found to be the best for both emissions and toll revenue objectives optimization. However, in both case studies, other parameters found to be sometimes negatively affected in the ‘Link Toll’ solutions compared to solutions obtained under the ‘Fixed Toll’ scenario.

It is worth mentioning that the emission cost calculated here (various emissions types into respective costs) should not be combined with direct cost like revenue, as the assumption of perfect substitutability is invalid when environmental objectives are considered(Wu et al., 2009). However, the emission cost has been estimated based on the present impact on humans and the environment by various emission types. This is to uplift the understanding, or the gravity of emissions and the conversion numbers may vary with time.

As mentioned earlier PPP are popular for developing new road infrastructure in Australia and thus the amount of revenue generated from toll charges is also a primary concern. Therefore, the above scheme shows promising results with respect to all concerns. In addition, higher user costs would lead to failure in the transportation system in the long
run and lower user costs achieved here is an added advantage. Considering both positives and negative points, the link toll scenario with the emission minimization objective can be proposed as a better toll scheme considering multi-stakeholder perspectives. It was believed in the past that minimizing both travel costs and reducing air pollutants could not be always achieved simultaneously (Zhang et al., 2010) and this study provides an example with more promising results.

8.5 Chapter summary

High toll charges force trucks to avoid quality roads, leading to increased emissions. A model is proposed in this chapter to find an effective toll charging scheme to minimize total network vehicular emissions while maintaining reasonable revenue for investors. A bi-level modeling approach is used, where toll prices for multi-class vehicles are decided in the upper level and user response to toll charges are predicted using user equilibrium (UE) conditions with multi-class traffic assignment in the lower level as described in Chapter 3. The model takes into consideration both toll revenue and total vehicle operating costs to produce an acceptable solution for both investors and road users. All major components of hazardous emissions (CO$_2$, PM2.5, SO$_2$ and NO$_x$) were considered and estimated using an emission cost model developed based on secondary data quantifying their impact on human health and the environment. This chapter is mainly focused on application of the model using both a small hypothetical network and a large real-world network with static demand conditions, under different toll charging scenarios. A genetic algorithm was used to find near-optima solutions for each toll-charging scenario. The results revealed that commonly used toll schemes are inefficient with respect to multi-stakeholder objectives. The toll charging scheme optimized using the GA was able to reduce the total emission cost of the network by 12% compared to the typical toll scheme currently used by a toll facility in a real network in Melbourne, Australia.
Chapter 9

Toll or Subsidy for Freight Vehicles on Urban Roads: A Policy Decision for City Logistics

9.1 Introduction

Delivering goods to cities using various type of freight vehicles is essential for maintaining cities economic and social functions. Nevertheless, it has received little attention from authorities in comparison to passenger movement (Holguín-Veras, 2010). Beyond the rational demand increase over time due to population growth in cities, there is an additional demand created for freight in urban transport networks as retail sector seeks to minimize its costs by saving storage space and reducing storage periods. Innovative supply practices such as just-in-time deliveries and tailor-made urban goods deliveries have also further increased demand for freight transportation. With the increase in urban goods transport, problems caused by city logistics have also
grown rapidly. Congestion, environmental problems due to emissions and noise, safety
problems, insufficient infrastructure (or insufficient maintenance) being typical
examples, among others (OECD, 2003). As a solution to the many problems
encountered, governments have decided to build quality roads since there are very
limited feasible solutions to manage city logistics. Since the public funding available to
government is not sufficient to fulfill such greater demands for road infrastructures, the
government made agreements with the private investors to build and operate roads
under public-private-partnerships (PPP). This PPP initiative for road infrastructure
development has become very popular around the world and is accepted by the public
as well due to its inherited advantages for all stakeholders.

In a PPP road project, the capital investment (including maintenance cost and profit) is
recovered from the toll revenue collected from the road users. On agreement papers,
toll charges are determined as a collaborative decision between the investors and the
authority. Nevertheless, it was found in the literature that higher toll charges were
placed in many facilities all over the world or disparity exist between the class of vehicles
(Holguín-Veras et al., 2006; Holguín-Veras and Cetin, 2009; Perera et al., 2016). On the
other hand, from the investor's point of view, they deserve a profit above the market
rate due to the massive long-term risks undertaken. The uncertainty involved in demand
forecasting and associated future revenues are the main risks faced by an investor in a
PPP project. In addition, number of contractual years in operation, political changes and
technological changes over time are also risks for an investor in a PPP project. Thus, one
of the important issues with PPP roads is to determine toll charges which have a direct
conflicting effect on major stakeholders (Yang et al., 2002; Yang and Meng, 2000). It is a
common practice in the world to make such toll decisions based on an economic model
with an explicit rationale. But with the vast experience of completing such similar
projects in this nature, Norwegians have now included socio-economic aspects (rather
looking at only financial terms) to their project evaluation feasibilities (Odeck, 2017)
highlighting the importance of all stakeholder aspects in a PPP project.

From the recent literature and the analysis carried out in this study, it is quite clear that
the present trend is to charge high tolls from road users, especially from heavy vehicles,
in order to maintain a high profit margin for their investments and to lessen their
payback period. Due to high toll prices, some road users tend to avoid toll roads by shifting to the local road network, which produces high externalities. However, toll avoidance is a common practice all over the world (McKinnon, 2006; Quak and van Duin, 2010; Yang et al., 2002) and aggravated as toll prices rise. In Melbourne, Australia, toll charges for commercial vehicles on a major toll road through the city has raised by more than 125% within the last two years. Since the Melbourne Metropolitan Region is known for heavy internal freight movement compared to the interstate freight movement by weight (Perera et al., 2017) and this toll increase made a significant impact on freight movement in and around the city.

Emissions, noise, accidents (crashes), congestion and infrastructure costs are considered as externalities and these externalities produced from vehicles have attracted general society’s attention now compared to past. The general public has now realized that even though they have no direct involvement in the operation of transportation, apparently, they are the whole bearers of such externalities. Therefore, some may argue that externalities need to be considered as an accrued expense, which shall be recovered from actual pricing policies to enable an efficient and sustainable freight transportation system (Demir et al., 2015). Since heavy vehicles produce many externalities compared to light vehicles (Cruz et al., 2012; Swan and Belzer, 2010) more attention has been put on the movement of heavy vehicles compared to light vehicles.

In this multiple stakeholder framework, however, investors need to give some priority with respect to returns they collect since otherwise whole PPP concept will fail sooner than later. As a result, there is clear evidence from the past and the present to think that toll charge only is not a good source of income for investors and its high time to look for other alternatives for a sustainable solution for this toll related problem. For similar problems with multi-stakeholders where the government is the leading stakeholder, subsidies have been considered along with the charges. As a result, a subsidy to the investor is proposed as the alternate option, which can provide a solution to multi-stakeholder problems identified above.

Subsidies can be seen ubiquitously in governments strategies to encourage either a system, process or product in any field such as in manufacturing, agriculture, food,
Toll or subsidy

health care, education, housing, fisheries, fuel, coal, transportation industries (Albers and Peeters, 2011; Schwartz and Clements, 1999; Smeeding et al., 1993). Subsidies given in agricultural industry in India (Fan et al., 2008), subsidies for renewable energy (Yu et al., 2016; Zhang et al., 2014), for energy efficient home appliance users in China (Yao et al., 2014), for sustainable land use (Arnalds and Barkarson, 2003), for child care in USA (Meyers et al., 2001), for re-manufacturing industry (Mitra and Webster, 2008), for entrepreneurship in USA (Li, 2002), for professional team sports in Australia (Wilson and Pomfret, 2009), for private spending on public goods (Roberts, 1992), for household biogas use in rural China (Sun et al., 2014), are few examples where subsidies have been used in the world other than in transportation. Similarly, subsidies are very common in the transportation field as well, especially in association with public transportation. Public transit subsidization is mainly to cover the deficits in operational costs (Sun et al., 2016) to make the public transport affordable for public and/or to promote public transportation as a solution to congestion or to control externalities (Serebrisky et al., 2009). Subsidised public transportation in USA (Pucher and Markstedt, 1983), France (Gagnepain and Ivaldi, 2002), Finland, Norway, Austria, Germany, Sweden, Belgium (Tscharaktschiew and Hirte, 2012), Chile, Argentina, Mexico, India (Serebrisky et al., 2009), Japan—(Zou and Mizokami, 2014) are few examples from the world. Not limited to public transport, subsidies are given for parking (Willson and Shoup, 1990), promoting non-motorised modes and less polluting vehicles (Buehler and Pucher, 2011), for batteries used in transportation (Viswanathan and Kintner-Meyer, 2011) as well in the transportation industry.

Even though subsidies have been used successfully in the transportation industry limited studies have looked at subsidies for investors as proposed in this study. Nevertheless, in the literature subsides in association with tolls and toll roads are discussed within the boundaries of user equity. This refers to toll amounts received from users or providing subsidies to users to maintain equity. Strategies like minimal-revenue congestion toll by Dial (1999), “credit allowance” concept by Kockelman and Kalmanje (2005), cashing out strategy proposed by DeCorla-Souza (1994), an equal travel allowances for all commuters by Small (1992), direct distribution approach proposed by Adler and Cetin (2001), price-and-rebate programs are some of the major contribution to organise such
subsidiess. However, the scope of this study is much broader and looking at how far subsidies to the investor can manage the multiple stakeholders in the toll rising problem. On the other hand, total cost optimisation principle has been studied under city logistics and have looked at implementation of urban consolidation centres, access control regulations to city centres, promoting off-peak hours deliveries, low emission zones, emission reduction models (Anand et al., 2012; Taniguchi et al., 2014), yet toll and subsidy approach to manage city logistics has not been received enough attention from past researchers.

Therefore, this study addresses the gaps of not implementing optimal toll charges on roads built under PPP to receive required revenue (which will minimize externalities) and how toll increase can be managed by means of government subsidies to the investor while maintaining sustainable city logistics. The optimal multi-class toll charges are identified for a given Internal Rate of Return (IRR) which can minimize externalities. Externalities are measured in dollar terms and subsidies are proposed to investors as recompense to the revenue loss. Mathematical models are developed in this study by considering the key stakeholder objective(s) and equilibrium solutions were explained. A numerical example (case study) was also used to illustrate the problem and optimum results are obtained using non-dominated sorting genetic algorithm II (NSGA II). Further, externalities are measured in the Australian context based on available data or if not directly extracted from literature after apposite conversion. Based on the results the policy decision of subsidies for road investors and what optimal toll scheme is suited for expected return are discussed with potential benefits.

The rest of the chapter is organized as follows. Section 9.2 explains the various common externalities and their impact on society or the environment in monetary terms. Section 9.3 covers the model development task by identifying the key stakeholders and their objectives. Section 9.4 provides the results and discussion based on the large network used in this thesis. Section 9.5 concludes the study outcomes given as Chapter summary.
9.2 Externalities

Externalities, which are mainly produced by heavy vehicles, include both environmental costs and social costs. Environmental costs include emission costs, and noise costs, while social costs comprise of accident costs (crash costs), congestion costs and infrastructure costs. There are two main challenges when calculating externalities. The first challenge is the estimation of contribution from each vehicle to individual cost element and the second is an estimation of the real impact on the environment or society in monetary terms (cost estimations). Few studies have addressed this issue in the past, mainly in Europe, but no comprehensive literature was found in the Australian context. In this study, some externalities are evaluated limited to the Australian context, but if data is lacking numbers are directly taken from European studies after appropriate conversion.

9.2.1 Crash costs

Escalating numbers of road traffic crashes have become a major concern all over the world. Road traffic crash deaths remain at about 1.2 million per annum globally (Devasurendra et al., 2017) and by 2030 will be the 5th leading cause of death in the world (Naumann et al., 2010). As a result, the losses caused by both individuals and society are significant (Abdel-Aty, 2003; Miller et al., 1997). The estimated economic cost of crashes in the US in 2010 was 242 billion USD (Blincoe et al., 2015) while in Australia it was estimated as 17 billion AUD in 2003 (Connelly and Supagan, 2006).

Crash costs consist of human cost component including quality lost in life (due to severe injuries), vehicle cost component and general cost component. Since vehicle cost and general cost components may reflect under direct costs or other externalities (e.g. travel delays under congestion cost), the main focus in crash cost calculation here is (as an externality) based on human cost, costs to the victims in pain and suffering (Demir et al., 2015).

The size of the vehicle, maneuverability and on-road loading/unloading operations are significant causes of heavy vehicle involvement in crashes. However, studies have proven that the number of heavy vehicles involved in crashes is less compared to the
other vehicle categories (due to a smaller number of heavy vehicles), but crash severities are generally high. As a result, when total crash cost is calculated contribution from heavy vehicles is not negligible. According to Brodie et al. (2009), heavy vehicles crash cost in Australia is about A$2 billion per year, which is about 12% of the total estimated cost.

Even though the crash cost assessment has a long history, yet the calculation is subjective. Nevertheless, the main objective of assessing such cost has been used as a tool to provide more cost-effective countermeasures and justification for the expenditures. Details about crash cost calculation are presented in Chapter 4.

### 9.2.2 Congestion costs

Congestion is by definition a condition of traffic delay. Therefore, congestion can be measured by a delay in trip time per individual or as a total. Since travel time is related to distance and speed, the average speed is an indirect way of measuring congestion, especially in urban cities. For example, in Singapore before application of congestion charging (before 1975) the average vehicle speed in CBD during peak hours was only 19kmph (Phang and Toh, 1997).

The concept of congestion as an externality is easy to understand but difficult to quantify. Various approaches have been taken in different studies in the past. Among them, the consideration of utility loss as a result of one being using the road can be given as the simple explanation used for congestion cost calculation. As a monetary figure, congestion cost in the USA was found to be 121 billion USD in 2011 (Fosgerau and de Palma, 2013).

It is a well-known fact that heavy vehicles create a significant impact on traffic flow due to its size and maneuvering limitations compared to cars and other light vehicles. This creates a physical effect on nearby vehicles leading to a reduction in true capacity. The psychological effect on other vehicle drivers due to adjacent heavy vehicle worsensthecacity reduction (Al-Kaisy et al., 2005). In addition, on-road loading and unloading operations may have intensified the condition. Recent research has found that the effect of heavy vehicles during congestion is significantly greater than that
during free flow condition (Al-Kaisy et al., 2005). Since roads are a scarce resource, congestion has affected the movement of essential logistics in the metropolis (Harriet and Poku, 2013). Therefore, it is worth to calculate the congestion cost generated by each vehicle on the road in order to minimize congestion cost under policy decisions. The calculation of congestion cost is presented in Chapter 4.

### 9.2.3 Infrastructure costs

Marginal road infrastructure costs correspond to the increase in road maintenance and repair expenditures that are induced by high traffic volumes. These effects can differ by country, road type, vehicle class, and the load carrying. Roads of higher quality, which usually require higher initial investment expenditure, have a longer life and are less prone to damage from increased traffic volumes.

In general, both marginal and capital infrastructure costs are paid by the government through central budgets with tax money. Thus, the road expenses certainly fall on the society/public that has no direct relevance to the operations of transportation. As a result, infrastructure costs need to be considered as an externality from transportation. For example, funding for Victoria’s road network comes from Federal, State and Local Government sources, except for privately operated freeways which are funded by the private owners and operators (VicRoads, 2018).

When the lifecycle of any infrastructure is concerned, the infrastructure costs can be broadly classified into three categories. Fixed cost, the capital investment that can be measured as per kilometer, by considering the number of lanes on the road or road capacity. Secondly, the variable costs and finally the profits are the three main categories. Variable costs can be of two folds. Routine maintenance costs (which includes administration costs as well) and periodical maintenance costs. Only routine maintenance cost elements can be apportioned to each vehicle type by the damage it caused and therefore measured as a cost per vehicle kilometer traveled. The periodic maintenance cost can be considered as a proportion of capital costs. The profit can be set out at any rate above the market rate in terms of Internal Rate of Return (IRR). However, this will be applicable only where private investors are involved in infrastructure developments (e.g. with Public-Private Partnership (PPP) projects). For
more information and calculation details about infrastructure cost please refer Chapter 4.

9.2.4 Emission costs

Greenhouse gas (GHG) emissions and air pollution are critical problems in many urban areas. Globally transport sector (road, air and water) is responsible for a large component of GHG emissions (Creutzig et al., 2011; Zeng et al., 2017) and road transportation is a major source of air pollution (Caiazzo et al., 2013; Chen and Yang, 2012; Dedoussi and Barrett, 2014; Galgamuwa et al., 2016a, 2016b). Among the road transportation emissions, freight transportation is responsible for the majority of the emissions, even though heavy vehicles only account for a small proportion of the total vehicle population (Iankov, 2016; Leenders et al., 2017; Wang and Rakha, 2017). Based on the most widely reported pollutants in vehicular combustion (Brugge et al., 2007; Fuller et al., 2012) PM2.5 and NOx have been found to have a significant negative impact on human health compared to other pollutants from vehicular emissions (Fuller et al., 2012; Malina and Scheffler, 2015; Zhu et al., 2002). Heavy diesel-powered engines (most trucks) are known to produce high levels of such PM2.5 and NOx compared to light petrol vehicles. Therefore, emission reduction is one of the major objectives considered in this study. Emission cost calculations are presented in Chapter 4.

9.2.5 Noise costs

The transportation-related noise pollution is mostly considered to be a nuisance for people that have to deal with it frequently. Past research has found that both severity and duration of noises cause health problems (e.g. sleep disturbance, stress, shot or long-term hearing loss and cardiovascular disease) (Cik et al., 2012; Kaddoura and Nagel, 2016). Increase in traffic volumes, especially with high noise making fleets (increases the severity of the noise), pushing heavy vehicles to operate during night times (by giving night time discounts on toll roads and implementing road curfews for trucks on many urban roads during day times) (which increases the duration of noise) have a major effect on those who live closer proximity to major roads. In the European Union, it is
claimed that around 20% of the population are exposed to environmental noise levels that health experts consider unacceptable (Day et al., 2006).

The negative impacts of noise on human health could cause various costs in terms of medical costs, costs of productivity losses, and the cost of increased mortality. However, due to the non-linear characteristics of noise pollution, the monetary estimation is complex (Martini et al., 2013). For detail noise cost estimation methods techniques, readers may refer (Andersson and Ögren, 2011; Day et al., 2006; Haling and Cohen, 1996; Lu and Morrell, 2006). Based on the available literature, the noise cost can be calculated and presented in Chapter 4.

9.3 Model development

In the toll-setting problem, the toll facility operator and the government are the main decision-makers, but there are many stakeholders interested in this problem in reality, as explained in Chapter 3. Therefore, the main stakeholders based on their key interests can be classified into three main categories; the toll road investor, road users (freight) and the general public. However, it should be noted that at the end of the day it is a government responsibility to protect all stakeholders in any problem in a reasonable manner. In this Chapter the same bi-level model developed in Chapter 3 is used to look at the toll problem form a different approach.

9.3.1 Stakeholder 1- Toll road investors

Since toll setting problem is a hierarchical problem, toll road investors have an upper hand to decide the toll charges for multi-class vehicles. Hence, they try to maximize the toll revenue in order to reduce their payback period and to maximize their return.

\[
\text{max}(TR) = \sum_{a} \sum_{m} T^m_a x^m_a
\]  

(9.1)

where

\[ T^m_a \] : Toll charge for each vehicle type for the given link \( a, a \in \overline{A}, m \in M \) (A$/km)
Toll or subsidy

Since it is a government responsibility to protect the road investors, the government might introduce a lower level of revenue so that investors will be retained in the long run. On the other hand, since high toll charges may adversely affect the road users’ government may introduce an upper limit to the revenue as well. As a result, the equation (9.1) and be re-expressed as;

\[ UL_{TR} \geq \sum_{a \in A} \sum_{m \in M} T_a^m \times x_a^m \geq LL_{TR} \quad (9.2) \]

where

- \( UL_{TR} \): The upper limit for the toll revenue (A$)
- \( LL_{TR} \): The lower limit for the toll revenue (A$)

The lower limit of the toll revenue (\( LL_{TR} \)) as well as the upper limit (\( UL_{TR} \)) can be determined based on the terms and the conditions of the PPP made with the government. However, the number of operational years given for the investor is another critical parameter when deciding toll charges (Odeck, 2017). Therefore, the equation (3.24) given in the Chapter 3 need to be considered in relation with equation (9.2) above. This mathematical formulation considers the net life cycle costs and benefits of the infrastructure development over the contractual period known as net present toll revenue (NPTR). Based on the equation (3.24), the Internal Rate of Return (IRR) is calculated which is the rate at which the net present toll revenue (NPTR) is equal to zero. IRR is one of the top project evaluation techniques not only in Australia, but also in many countries of the world (Truong et al., 2008) and hence used in this study. To avoid any confusion that may occur in IRR calculations, IRR is only calculated when NPTR is positive (\( r>0 \)) and since all inflows are positive, positive IRRs are obtained.

\( Y \) is a time period agreed initially to transfer the project, usually to the government. In Melbourne, both CityLink and EastLink have given operation years approximately 34 and 35 years respectively (this is after construction) and it’s usually 15-17 years in Norway. However, this ‘\( Y \)’ value is negotiable and may change even at a later time as per the agreements made.
In this study, it was assumed that the fixed demand condition is typical for a peak one hour and it would continue throughout the years. The following assumptions are also made to calculate the IRR rates under different toll schemes for both case studies. It is assumed that, \( FM_a(C_a) = \alpha I_a(C_a) \), where \( 0 < \alpha \leq 1 \). This implies that the fixed maintenance cost per year is considered as a fixed percentage of the capital cost of the infrastructure. Here, \( \alpha \) is assumed to be 0.01. It was assumed that toll roads operate for 24 hours a day where peak hour volume is equal to 10% of AADT Average Annual Daily Traffic). Capital costs of construction were considered to be A$ 65.8 million/km (or a 4 lane freeway) based on EastLink construction costs of A$ 2.5 billion for a 39km stretch (Perera et al., 2016). The period of operation was considered as 39 years for EastLink (for CityLink its 34 years) before transferring to the client.

### 9.3.2 Stakeholder 2 - Vehicle users

Once the toll prices are set, users react by setting up their route such that the total travel cost, i.e. standard operating costs (time, distance, etc.) is minimized. The toll charges are not included in the travel cost due to two reasons. The first reason is that route choice is mostly made by the users by looking at operating costs saving and the respective toll charges. Therefore, their primary consideration is on operating cost. And secondly, toll revenues are already considered under the investors’ objective and the amount will be duplicated if used here. From the government perspective, the government does not favor any of the freight users and thus try to minimize the total operation cost aiming at sustainable transportation. Therefore, total operation costs (User cost) can be mathematically expressed as equation (3.1) given in Chapter 3. Equation (3.1) explains the minimization of summation of all the operating costs incurred by all users operating in the network. This includes each individual’s vehicle operation cost with respect to time and distance. Vehicle operation cost estimates used in this study are taken from the author’s previous work published (Yang et al., 2016).
9.3.3 Stakeholder 3- Residents, other road users and general public

The third main stakeholder can be considered as the general public who consist of residents and other road users (other than freight users). The general public’s perspective is to minimize the externalities produced by the entire network. Unlike the investors, it is important to note that the public would look at the entire network as a whole, not only a specific link. Therefore, equations (3.2 and 3.3) presented in Chapter 3 explains the social and environmental cost generated by each vehicle on this network.

9.4 Results and discussion

Costs in transportation can be broadly divided into two, known as direct costs and indirect costs (sometimes referred to as externalities). Indirect costs mainly comprised of emissions cost, noise cost, crash cost, infrastructure cost and congestion cost but not limited to. The direct costs are paid by the users’ and indirect costs generated from transportation has been paid by the general public and the government. Since government money is ultimately from the general public, the total indirect costs of transportation have been finally paid off by the general public. In the present context, the general public is more aware of this situation and demand for better policies. At the same time, road users also now demand better usage-based charges replacing indirect charges such as fuel taxes and other levies. From users’ point of view, this usage-based charging would enable proper costing of transportation of goods and people eliminating two major discrepancies. One being the cross-subsidization of public funds to develop/maintain road infrastructures and other being transferring externalities to the society. Since this study is more focused on price (toll) charged on freeway roads a comparison is presented below showing actual costs when using a freeway (toll road) from the city of Melbourne.

From the cost model developed to calculate externalities, various costs are calculated for multi-class vehicles on a freeway link considering various traffic conditions and are shown in Table 9.1.
Table 0.1: External costs for multi-class vehicles on freeways under various traffic conditions

<table>
<thead>
<tr>
<th>Vehicle Type</th>
<th>Emissions Cost (A$/km)</th>
<th>Noise Cost (A$/km)</th>
<th>Crash Cost (A$/km)</th>
<th>Infrastructure Cost (A$/km)</th>
<th>Congestion Cost (A$/km)</th>
<th>Total Cost (A$/km)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>(a) Un-congested traffic condition (average speed= 100km/hr)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Car</td>
<td>0.0377</td>
<td>0.0321</td>
<td>0.0088</td>
<td>0.0035</td>
<td>0.0000</td>
<td>0.0821</td>
</tr>
<tr>
<td>Short</td>
<td>0.1005</td>
<td>0.1605</td>
<td>0.0064</td>
<td>0.0052</td>
<td>0.0000</td>
<td>0.2726</td>
</tr>
<tr>
<td>2 Axle Truck</td>
<td>0.1288</td>
<td>0.1605</td>
<td>0.0076</td>
<td>0.0277</td>
<td>0.0000</td>
<td>0.3246</td>
</tr>
<tr>
<td>3 Axle Truck</td>
<td>0.3672</td>
<td>0.1605</td>
<td>0.0076</td>
<td>0.0382</td>
<td>0.0000</td>
<td>0.5735</td>
</tr>
<tr>
<td>4 Axle Articulated</td>
<td>0.4982</td>
<td>0.2949</td>
<td>0.0121</td>
<td>0.0485</td>
<td>0.0000</td>
<td>0.8537</td>
</tr>
<tr>
<td>5 Axle Articulated</td>
<td>0.5074</td>
<td>0.2949</td>
<td>0.0121</td>
<td>0.0572</td>
<td>0.0000</td>
<td>0.8716</td>
</tr>
<tr>
<td>6 Axle Articulated</td>
<td>0.5452</td>
<td>0.2949</td>
<td>0.0121</td>
<td>0.0347</td>
<td>0.0000</td>
<td>0.8869</td>
</tr>
<tr>
<td>B Double</td>
<td>0.6526</td>
<td>0.2949</td>
<td>0.0121</td>
<td>0.0555</td>
<td>0.0000</td>
<td>1.0151</td>
</tr>
<tr>
<td>Double Rd Train</td>
<td>0.7329</td>
<td>0.2949</td>
<td>0.0121</td>
<td>0.0746</td>
<td>0.0000</td>
<td>1.1145</td>
</tr>
<tr>
<td>Triple Road Train</td>
<td>0.9186</td>
<td>0.2949</td>
<td>0.0121</td>
<td>0.1370</td>
<td>0.0000</td>
<td>1.3626</td>
</tr>
<tr>
<td><strong>(b) Near capacity traffic condition (average speed= 90km/hr)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Car</td>
<td>0.0349</td>
<td>0.0132</td>
<td>0.0088</td>
<td>0.0035</td>
<td>0.4647</td>
<td>0.5251</td>
</tr>
<tr>
<td>Short</td>
<td>0.0939</td>
<td>0.0660</td>
<td>0.0064</td>
<td>0.0052</td>
<td>0.4647</td>
<td>0.6362</td>
</tr>
<tr>
<td>2 Axle Truck</td>
<td>0.1130</td>
<td>0.0660</td>
<td>0.0076</td>
<td>0.0277</td>
<td>0.8826</td>
<td>1.0969</td>
</tr>
<tr>
<td>3 Axle Truck</td>
<td>0.3271</td>
<td>0.0660</td>
<td>0.0076</td>
<td>0.0382</td>
<td>0.8826</td>
<td>1.3215</td>
</tr>
<tr>
<td>4 Axle Articulated</td>
<td>0.4419</td>
<td>0.1215</td>
<td>0.0121</td>
<td>0.0485</td>
<td>1.3456</td>
<td>1.9696</td>
</tr>
<tr>
<td>5 Axle Articulated</td>
<td>0.4552</td>
<td>0.1215</td>
<td>0.0121</td>
<td>0.0572</td>
<td>1.3456</td>
<td>1.9916</td>
</tr>
<tr>
<td>6 Axle Articulated</td>
<td>0.4922</td>
<td>0.1215</td>
<td>0.0121</td>
<td>0.0347</td>
<td>1.3456</td>
<td>2.0061</td>
</tr>
<tr>
<td>B Double</td>
<td>0.5976</td>
<td>0.1215</td>
<td>0.0121</td>
<td>0.0555</td>
<td>1.3456</td>
<td>2.1323</td>
</tr>
<tr>
<td>Double Rd Train</td>
<td>0.6762</td>
<td>0.1215</td>
<td>0.0121</td>
<td>0.0746</td>
<td>1.3456</td>
<td>2.2300</td>
</tr>
<tr>
<td>Triple Road Train</td>
<td>0.8550</td>
<td>0.1215</td>
<td>0.0121</td>
<td>0.1370</td>
<td>1.3456</td>
<td>2.4712</td>
</tr>
<tr>
<td><strong>(c) Congested traffic condition (average speed= 70km/hr)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Car</td>
<td>0.0312</td>
<td>0.0132</td>
<td>0.0088</td>
<td>0.0035</td>
<td>1.0664</td>
<td>1.1231</td>
</tr>
<tr>
<td>Short</td>
<td>0.0853</td>
<td>0.0660</td>
<td>0.0064</td>
<td>0.0052</td>
<td>1.0664</td>
<td>1.2293</td>
</tr>
<tr>
<td>2 Axle Truck</td>
<td>0.0893</td>
<td>0.0660</td>
<td>0.0076</td>
<td>0.0277</td>
<td>2.0270</td>
<td>2.2176</td>
</tr>
<tr>
<td>3 Axle Truck</td>
<td>0.2675</td>
<td>0.0660</td>
<td>0.0076</td>
<td>0.0382</td>
<td>2.0270</td>
<td>2.4063</td>
</tr>
</tbody>
</table>
In Table 9.1 emission costs are high for all vehicle types when running at higher speeds. This is mainly due to the fuel efficiency of vehicles with respect to speeds. Since the optimal fuel-efficient speeds are around 70km/hr for all types of vehicles the emission cost is less around such speeds. Noise cost makes a significant difference based on whether roads are congested or not since beyond some limit noise has less added effect on humans. Crash cost and infrastructure cost is not changing as traffic condition changes since both cost elements have no relationship with neither the traffic condition nor the speed. However, one may argue that crash costs need to be related to the speed of the vehicle (it’s a well-known fact that crash severities are related to vehicle speed), but unfortunately, the present data and studies have not supported such advanced features. The total costs under various conditions determine the maximum external cost a vehicle would experience under given traffic conditions. This doesn’t mean that all externality costs need to be charged as a toll and shall be given to investors, but the point is users are the responsible party for such costs, not the society. How the revenue collected to compensate externalities and how that money will be utilized is a different topic and not within the scope of this paper. Infrastructure cost determines the minimum cost that the investor should charge from users in order to recover their maintenance (variable) costs. Or in other words, infrastructure cost reflects the damage caused by each vehicle type to the road pavement. Thus, the optimal toll for investors point of view would be infrastructure cost plus a margin to cover the capital cost, fixed maintenance cost, anda profit. As expected, infrastructure cost is high when the number of axles is increasing (Chou, 1996; Dodoo and Thorpe, 2005; Fowkes et al., 1992; Sathaye et al., 2010) but no significant relationship exists with the speed of the vehicle.

Figure 9.1 and 9.2 depict how toll charge per kilometer (km) vary with trip distance (on a toll road) for a heavy commercial vehicle (HCV) on Melbourne EastLink and CityLink.
The toll charging trend lines based on trip distances for both toll roads look similar, but the magnitudes are different for two toll roads. In common, it can be seen from both figures that most of the shorter trips (less than 5 km) are charged heavily. Overall the minimum charge is 0.43 A$/km for EastLink and 0.91 A$/km for CityLink. The maximum toll charge is 1.95 A$/km and 4.60 A$/km for EastLink and CityLink respectively. When compared to similar calculations carried out in the previous studies (Perera et al., 2016) it can be seen that overall toll charges have risen by 5% for EastLink whereas it is 69 to 141 percent increase can be seen for CityLink during last two years, for HCV. This clearly shows that there is a significant price disparity between two toll roads in Melbourne and how it may affect freight transport is elaborated in this study.

When comparing the numbers from Table 9.1 and toll prices in EastLink as shown in Figure 9.1, it indicates that present toll charges in EastLink are more expensive than the pavement damage (infrastructure cost) caused by each vehicle type and it’s even beyond the total externalities price sometimes. When CityLink toll prices are compared it’s significantly higher than the pavement damage as well as the externalities. Therefore, it can be concluded that present toll charges in Melbourne for multi-class freight vehicles are higher than they should be, which supports the literature. Nevertheless, investors on toll roads take higher risks when investing on a toll road project like EastLink or CityLink and thus it is fair and reasonable that investors need to be given a better opportunity to recover their money. Having said that it doesn’t necessarily mean that investors should be allowed to charge whatever price they want, to recover their investment fast which may threaten sustainable transportation. As a result, there should be an optimal condition considering infrastructure cost, operational cost and externalities along with the toll revenue. Since high toll charges tend to make trucks to avoid toll roads and shifting to low-quality roads producing more externalities, rest of this paper looks at how government can intervene and set up better prices (tolls) for freight vehicles considering ‘total optimization’ as explained in City Logistics (Taniguchi and Thompson, 2014).
Figure 0.1: Toll charge per km for a heavy commercial vehicle on EastLink (North-South direction)

Note: This was based on toll charges published by eastlink.com.au for the year-end in June 2018

Figure 0.2: Toll charge per km for a heavy commercial vehicle on CityLink (Daytime, North-South direction)

Note: This was based on toll charges published by citylink.com.au for the quarter from April to June 2018
Table 9.1 depicts the externalities produced for freeways only. However, a typical city road network consists of freeways, highways and other roads allowing users to select various routes to reach their destinations. Therefore, it is not reasonable to arrive at conclusions just by looking at costs incurred on freeways only. The next section of the paper looks at the overall impact of various toll charging schemes from a network perspective. For this analysis road network around EastLink is used as introduced above and three arbitrary toll schemes are used for illustrative purposes.

**Toll Scheme 1:** Fixed, distance-based toll charges were applied to all vehicle types to see the impact generated from the network. This is the simplest toll charging scheme that can be implemented on a road section without many practical difficulties. In other words, one charge per km is charged from all types of vehicles irrespective of its size, number of axles, or considering any other parameter. However, light vehicles would not like the fixed distance-based charging scheme due to equity issues. But it is used in this study as the first toll scheme to demonstrate the network behavior with tolls.

Figure 9.3 depicts the variation in operation costs, externalities, and toll revenue with respect to toll scheme 1 applied to the real network. Results show that higher toll charges will always end up producing higher externalities similar to total operating cost. Between A$ 0.5/km to A$ 1.35/km externalities are increasing drastically at a very higher rate whereas operation costs increase at a constant rate throughout. However, the toll revenue increases drastically when tolls are cheap (up to A$ 0.85/km) and after reaching a maximum point it turns around. This figure clearly shows that high toll charges would not necessarily generate higher toll revenue, in fact, high impacts in terms of externalities and operation cost. Overall, when toll prices are reaching towards the extreme point there will be substantial generation of negative impacts in terms of externalities and operation costs hindering users and public acceptance. In addition, due to the drop in the toll revenue after A$ 0.85/km toll charge, investor acceptance rates will also diminish. Thus, high toll charges tend to produce less sustainable solutions which are not accepted by stakeholders.
The above analysis explicitly shows us that the conditions are more complex and need to be handled carefully to arrive at an equilibrium point where all stakeholders can reasonably agree. However, this is just a general application of toll charges to demonstrate the outcomes with respect to revenue and costs. From the results, it is very clear that even a high flat toll would not give the maximum return to the investors. On the other hand, a high flat charge will not be accepted by cars and LCV’s users considering their size, less space occupancy on roads and lesser damages they caused to the roads compared to HCV’s. As a result, a scheme which would address such equity issues will be most desirable.

**Toll scheme 2:** The present EastLink toll scheme has a limited number of classifications with respect to vehicle type, namely, cars, light commercial vehicles (LCV), heavy commercial vehicles (HCV) and motorbikes for charging purposes. In addition, the rates follow 1: 1.6: 2.65 ratios between cars, LCV’s and HCV’s respectively. Considering the same ratios and extreme toll boundaries for HCV’s (depicted in Figure 9.1), all possible toll schemes were applied to the real network and the outcomes are shown in Figure 9.4 and 9.5.
All toll rates generated positive toll revenues and when the high rates have applied, the rate at which toll revenue increases reduces. Externalities tend to increase gradually when toll charges are increasing but rapid increases can be seen when toll charges are between A$ 0.60/km to A$ 1.00/km and A$ 1.50/km to A$ 1.70/km. Therefore,
increasing toll schemes to generate extra profit for the investor is not advisable beyond a certain level (A$ 1.54/km) since revenues decline at the expense of increasing externalities.

Figure 9.5 denotes the IRR vs toll charge for HCV. The IRR is a form of estimating the rate of return obtained from toll revenue considering more parameters such as numbers of years in operation and infrastructure cost (fixed and variable maintenance cost). The IRR is one of the top project evaluation criteria not only in Australia but also in many countries of the world (Truong et al., 2008). It is clear from the Figure that all toll rates (even the minimum toll charge) are making positive IRR percentages and even reach a maximum of 24%. Considering the cost of capital in Australia, which is between 5-6% (Truong et al., 2008), almost all the toll schemes are making positive profits from EastLink roads. As mentioned above, EastLink toll charges are fairly low compared to the CityLink toll charges and thus CityLink is making supernormal profits.

The two toll scenarios presented above clearly illustrate the present problem of high toll charges on freight vehicles and the negative consequences produced in terms of large externalities and high user charges. Therefore, there is a necessity for transport planners/researchers to intervene and find an optimal solution where all parties can be reasonably agreed.

Since PPPs are more popular and the government wants to undertake more and more PPP road projects in the future, investor satisfaction is at the top of the government priority list. At the same time, it's the government responsibility to safeguard users as well as the general public and to maintain a sustainable transportation system in cities. Therefore, the government should consider alternative ways of managing all these stakeholders in an efficient manner. As explained earlier government subsidies to investors is considered in this study as an alternative to maintaining sustainable transportation while managing stakeholders. The rest of this chapter looks at the application of subsidy and how it can solve this problem and related issues. Illustration 1 below depicts how subsidies can be used in the simplest way to address the toll problem discussed here.
**Illustration 1:** Let’s assume a toll investor wants to make around A$ 137,000 revenue (IRR=19%) from the toll in EastLink network discussed above. In such circumstance, they would end up charging 0.38, 0.61 and 1.01 A$/km from cars, LCV’s and HCV’s respectively under the prevailing EastLink toll ratio (Toll scheme 2). But we propose there is a better way of handling this by the authorities in the form of providing subsidies to the investors. Table 9.2 shows the trade-offs.

**Table 0.2:** Different toll rates and trade-offs

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Toll Charge (A$/km)</th>
<th>Toll Revenue (A$)</th>
<th>Total Externalities (A$)</th>
<th>Total Operation Cost (A$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current</td>
<td>0.38 0.61 1.01</td>
<td>137,262</td>
<td>3,392,474</td>
<td>901,089</td>
</tr>
<tr>
<td>Proposed</td>
<td>0.19 0.30 1.50</td>
<td>94,511</td>
<td>3,162,973</td>
<td>890,799</td>
</tr>
<tr>
<td>Difference</td>
<td></td>
<td>42,751</td>
<td>229,501</td>
<td>10,290</td>
</tr>
</tbody>
</table>

This illustration shows that in order to earn A$ 137,262 by the investor, the investor needs to apply the current toll scheme which produces A$ 3,392,474 worth externalities with an operating cost of A$ 901,089. With the government intervention, if the proposed toll scheme is applied, the investor will be earning A$ 42,751 less than their expected revenue. If this deficit is paid by the government as a subsidy to the investor, the total saving from both externalities and operation cost would be about A$ 239,791. This saving is about 5.6 times the subsidy payment and users will also be happy due to the reduction in toll charges. When numbers are compared this is a much better strategy considering all three major stakeholders.

However, it is worth mentioning that the externalities calculated here (various components into respective costs) should not be combined or compared with direct costs or revenue, as the assumption of perfect substitutability is invalid when environmental and social objectives are considered (Wu et al., 2009). Therefore, the numbers are used for comparison purpose based on the present impacts estimated from such environmental and social elements.

Nevertheless, this proposal still does not provide a good solution for freight operators since HCV are charged highly compared to others (since the same toll ratio is still maintained as EastLink). Therefore, various combinations of toll rates need to be
evaluated without sticking to the ratios used by EastLink in order to find more acceptable, efficient solutions. As a result, toll scheme 3 is introduced as follows.

**Toll scheme 3:** A large number of un-tied toll schemes (no fixed toll ratio) are applied to the network maintaining the toll boundaries specified above.

The optimum toll schemes are selected using an elitist non-dominated sorting genetic algorithm (NSGA II). Figure 9.6 depicts the Pareto optimal solutions obtained considering three main objectives. For clarity purposes, 2-dimensional view of the Pareto-front with respect to ‘Toll revenue vs Externalities’ and ‘Toll revenue vs Operation cost’ are presented in Figures 9.7 and 9.8.

![Figure 0.6: Pareto-optimal front for three objectives: Toll Revenue, Externalities and Operation Costs](image)

The Pareto optimal solutions are (any point given in this Pareto-front is a solution) unique compared to other solutions. No solution is dominated by another solution and the whole range of solutions are available to the decision maker to choose one solution based on their choice. The decision maker can make a decision on what toll scheme is quite suitable for the system based on prevailing policies and prioritized interests of the
stakeholders. For example, let’s assume the government wants to achieve a minimum operating cost with a toll revenue around A$165,000 neglecting the externalities produced. The best toll scheme to provide such conditions would be the toll scheme highlighted in Figure 9.8, which also be the lowest externality producing solution under given constraints. Why this toll scheme is the best under given conditions can be explained as follows. The Pareto-front shows only the non-dominated points where there could be many solutions which can provide the same total operation costs but with lower toll revenue and higher externalities.

![Figure 0.7: Toll revenue vs Externalities](image_url)
Figure 9.6 clearly shows the trade-offs with externalities and total operation cost as toll revenue increases. However, among all possible solutions given in the Pareto-front, some toll schemes might get criticized by users due to reasons such as equity. For example, if large trucks (4 axle and 6 axle trucks) are charged much less compared to cars, car users may not be willing to accept such toll charges since it is well known that trucks generate more impacts compared to cars in every aspect, such as pavement damage, space utilization, etc. This will be the main challenge in implementing toll charges optimizing overall impact which need to be handled differently. Two toll schemes are selected and compared with extreme revenue generating toll scheme to illustrate (illustration 2) the significance of offering a subsidy to investors considering network-wide impacts.

**Illustration 2:** Let’s assume the investor wants to make the maximum possible revenue (extreme revenue) from this project and how subsidies can help to minimize the trade-offs. Two proposals are used in this illustration where ‘Proposed 1’ toll scheme is on the high side of the toll charges where ‘Proposed 2’ toll scheme presents lower charges for
all vehicle classes comparatively. For both proposed toll schemes, the subsidy payment required and respective savings from externalities and operation cost are calculated and presented in Table 9.3.

### Table 9.3: Comparison of proposed toll schemes with extreme revenue toll scheme

<table>
<thead>
<tr>
<th>Toll Scheme</th>
<th>Toll Charge (A$/km)</th>
<th>Toll Revenue (A$)</th>
<th>Externalities (A$)</th>
<th>Total Operation Cost (A$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Car</td>
<td>2 Axle</td>
<td>4 Axle</td>
<td>6 Axle</td>
</tr>
<tr>
<td>Extreme Revenue</td>
<td>0.91</td>
<td>0.85</td>
<td>0.79</td>
<td>0.68</td>
</tr>
<tr>
<td>Proposed 1</td>
<td>0.79</td>
<td>0.74</td>
<td>0.66</td>
<td>0.55</td>
</tr>
<tr>
<td>Proposed 2</td>
<td>0.86</td>
<td>0.58</td>
<td>0.35</td>
<td>0.10</td>
</tr>
</tbody>
</table>

### Table 9.3 Continued

<table>
<thead>
<tr>
<th>Toll Scheme</th>
<th>Subsidy (A$)</th>
<th>Savings</th>
<th>Total Operation Cost (A$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Externalities (A$)</td>
<td></td>
</tr>
<tr>
<td>Extreme Revenue</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Proposed 1</td>
<td>4,826</td>
<td>110,753</td>
<td>2,941</td>
</tr>
<tr>
<td>Proposed 2</td>
<td>54,691</td>
<td>306,792</td>
<td>12,798</td>
</tr>
</tbody>
</table>

From proposal 1, the amount needed to be paid as subsidy is less compared to proposal 2, and savings from externalities and operation cost are high compared to the subsidy payment. However, toll charges in proposal 1 are generally high compared to proposal 2 where overall user acceptability is high for proposal 2 compared to proposal 1. For Proposal 2, the subsidy payment is relatively high compared to the subsidy payment required for proposal 1 and at the same time savings from both externalities and operation cost are also significantly high compared to the similar savings from proposal 1. As illustrated, there are many toll schemes available for the government to select under the prevailing circumstances to achieve better optimal condition with toll charges with subsidies.
9.5 Chapter summary

Toll roads constructed under public-private-partnerships (PPP) are very common around the world. Due to the high capital cost invested and high risks associated with subsequent returns, investors are concerned about future returns. As a result, the present trend is to charge high tolls for freight vehicles, especially in urban areas, which has created many problems not only economic but from a social and environmental viewpoint as well. It is a well-accepted principle that users need to pay for what they have used, but the price must be fair for all. This theory applies to road usage as well. However, the toll charge for freight vehicles was found not to be proportional to the damage it causes to infrastructure, environment and society. As a result, freight vehicles tend to deviate from freeways (toll roads) to second best roads (highways and arterial roads) in order to minimize their costs but this produces more costs for society and the environment.

This problem has multiple stakeholders with multi-objectives and needs to consider everyone’s concerns when looking at a sustainable solution for City Logistics. Therefore, this Chapter investigates various cost elements (economic, social and environmental) involved with freight movement in cities and compares with one of the existing toll structures of a toll road in Melbourne. A step by step process is followed in this study with illustrations to explore the best toll charging scheme considering various toll scenarios within a multi-objective framework. When considering the overall impacts, this Chapter identifies a tolling scheme with subsidies as the best option to minimize the total cost of urban freight transport which can lead to more sustainable city logistics in the future.
Chapter 10

Stakeholder Acceptance of Optimum Toll Schemes

10.1 Introduction

Beyond the economic viewpoint of looking at projects’ success, the world is moving towards considering more qualitative measures such as environmental and social factors known as externalities. In the freight transportation industry, most stakeholders are affected by externalities and stakeholders voice has become stronger and active over time where policymakers cannot ignore their demands anymore (Haezendonck, 2008). Many innovative City Logistics concepts have been failed due to non-consideration of all stakeholders into the decision-making process (Macharis et al., 2014). As a result, evaluation methods have evolved over time from cost-effectiveness analysis (CEA) methods to economic-effects analysis (EEA) to social cost-benefit analysis (SCBA) and finally multi-criteria decision analysis (MCDA) (Macharis, 2005; Macharis et al., 2009). However, due to the uncertainty involved in assessing external effects in monetary terms, evaluation methods like SCBA have failed to produce consistent results.
There is a clear need for a comprehensive approach to evaluating urban freight solutions in order to assess their chance of success and Multi-Criteria Decision Analysis (MCDA) provides a good framework to evaluate different transport options on several criteria. This is no longer a new idea and many methods have developed to accommodate such Group Decision Support Systems (GDSS) (Macharis, 2005). Multi-Actor Multi-Criteria Analysis (MAMCA) framework developed by Macharis, (2007, 2000) is an extension of the existing multi-criteria analysis. The MAMCA methodology differs from the classical MCDA because in MAMCA stakeholders are explicitly involved throughout the steps in the appraisal process (Hadavi et al., 2018).

MAMCA is a methodology to evaluate different policy measures whereby different stakeholders’ opinions are explicitly taken into account. MAMCA has been tested and used to evaluate a number of transport-related strategic decisions in the past (Macharis, 2007), especially in freight transportation. For instance, ‘Flanders in Action’ project, which was initiated to turn Flanders into a top region in terms of mobility and logistics (Macharis et al., 2010), assessment of various alternative ring ways for a regional freight route in Flanders Region, Belgium (Vermote et al., 2013), real-time monitoring of the cargo being transported using GPS (Macharis et al., 2014), off-hour deliveries in Brussels (Verlinde and Macharis, 2016), last mile delivery options (Aljohani and Thompson, 2018; Verlinde et al., 2014) are few past studies, but not limited to mention.

Since the MAMCA methodology has already proven its effectiveness in evaluating complex, sustainable mobility and transport policy decision (Hadavi et al., 2018), MAMCA has been used in this study to solve another timely City Logistics problem. The rest of the Chapter is organized as follows. Section 2 defines the problem that needs to be solved and Section 3 discusses the possible alternatives. Section 4 is intended to discuss the relevant stakeholder, their objective and priorities with respect to the given problem and Section 5 outline the MAMCA framework in brief. Section 6 presents the results and discussion of the MAMCA application and Section 7 provides the concluding summary of the study.
10.2 Problem Definition

The primary objective of the freight carriers is to maximize profit and operation cost minimization is one of the major approaches to achieve it. As a result, freight vehicle routes are generally determined by considering the individual cost of operation. At the same time, road tolls are set by service providers, mostly in collaboration with authorities to recover investment cost plus a profit at the market rate. Since toll charges increase carriers cost of operation, they tend to avoid such roads but to look for alternative roads, mostly arterial or local. The change in delivery times known as off-hour-deliveries are found to be not an option based on past studies (even though no tolls or reduced charges at nights). It is important to note that freight vehicles produce more externalities compared to light vehicles and varies profoundly on road type and speed. Therefore, the toll can lead to producing more cost to the society in terms of emissions, noise, air quality (environmental factors), road safety, crashes and congestion (social issues), unless properly managed. More information about the problem and related issues are presented in Chapters 1 and 2.

As explained above this transportation problem has multiple stakeholders involved as depicted in Figure 10.1. On the left-hand side of Figure 10.1 key stakeholders involved in this problem are listed where on the right-hand side of the figure shows the impacts generated through the decision made satisfying various stakeholder objectives. As the decision support tool, this study has developed a mathematical model to generate optimum toll charges under various conditions. Since there are multiple stakeholders and multiple objectives to achieve there is no such single solution which satisfies all stakeholders. Therefore, there are various solutions generated optimizing the toll charges considering various objectives which can be selected by the decision maker considering the given conditions. However, their overall acceptability from all stakeholders is questionable. Therefore, as the last step in this research MAMCA technique is used to evaluate the optimized toll schemes to find the best-accepted ones. The solutions considered in this study are listed under ‘Toll Policies’ section (Section 10.3).
In this toll optimization study, various objectives are optimized using a bi-level model to find out the optimum toll scheme for the given conditions. The objectives are sometimes taken directly from stakeholder objectives and sometimes it’s a combination of two or few stakeholder objectives. The outcomes from such toll schemes are evaluated using two networks. The first network is a hypothetical network and the second one is a real network around EastLink in Melbourne. In addition, different popular toll schemes are also evaluated using both networks and results are analyzed (see Chapters 7 & 8 for more details).

The following toll schemes are selected for evaluation purpose from the hypothetical network results. All toll schemes have considered distance-based toll charge, where toll charge rate in A$/km for a particular vehicle type is fixed for all links in the network. However, under this method, different vehicles may be charged at a different rate unless a specific toll ratio is applied for multi-class vehicles. The distance-based toll charging
scenario is one of the popular and common methods used around the world (Gammelgaard et al., 2006; Jou et al., 2012; O’Mahony et al., 2000), due to its simplicity.

Alternatives considered are as follows;

1. **Minimum Emission cost toll scheme** - This toll scheme would minimize the total emission cost of the network

2. **Minimum Environmental cost toll scheme** - This toll scheme would minimize the total environmental cost (emission cost + noise cost) of the network

3. **Minimum Social cost toll scheme** - This toll scheme would minimize the total social cost (crash cost + congestion cost + infrastructure cost) of the network

4. **Min User cost toll scheme** - This toll scheme would minimize the total user cost which is including toll charges.

5. **Max revenue toll scheme** - This toll scheme would generate the maximum toll revenue from the network under given demand conditions.

6. **Optimum 1 toll scheme** - This toll scheme is chosen from the Pareto front developed under multi-objective (3 objectives) optimization. The IRR for this toll scheme is greater than 20% (IRR > 20).

7. **Optimum 2 toll scheme** - This toll scheme is also chosen from the Pareto front developed under multi-objective (3 objectives) optimization. In this toll scheme, the IRR is just above 5% (5 < IRR < 10).

8. **Typical toll scheme** - This toll scheme is developed based on the present toll charging level in CityLink, Melbourne. CityLink freeway in Melbourne has variable toll charges for various sections for any type of vehicle, but the ratio between multi-classes are kept constant. The same toll ratio, which is 1: 1.6: 3
for cars: light commercial vehicle (LCV): heavy commercial vehicle (HCV) is used in this study assigning the maximum toll charge for HCV as A$ 2.55.

9. **Minimum Operation cost toll scheme**- This toll scheme would minimize the total operation cost (vehicle operation cost (including time cost)) of the network.

10. **Maximum Toll scheme**- this is the highest charged toll scheme. All vehicle types are charged A$ 2.55. this toll scheme is considered for comparison purpose and not taken from the model results (no optimization has applied)

Parametric values obtained for the above alternatives are given in Appendix 10a.

### 10.4 Stakeholders, objectives and priorities

According to Banville et al., (1998) stakeholders in the context of transportation (policy) can be defined as “those people who have a vested interest in a problem by affecting it or/and being affected by it”. In this problem, freight operators, government (or local authority) toll operators, and residents found to be the key stakeholders since carriers and shippers are more related to the freight operators. More details about stakeholders, their objectives and problems are presented in Chapters 2 and 6.

An in-depth understanding of each stakeholder group’s objectives is critical in order to appropriately assess the different alternatives (Hadavi et al., 2018) and there are two ways to achieve this. First is to ask a few professionals who have a good understanding of the problem (project) and follow the pair wise comparison to arrive at respective weights. Secondly, by conducting a survey to collect responses from each stakeholder group regarding their objectives. The first method is much easier to organize and coordinate, less time consuming and less costly than the second method, but the outcome could also be less superior.

Therefore, in this study, a survey was carried out to collect stakeholder information as much as possible, but the first method has been used where stakeholders are not
reachable or not responding. For more information about the survey please refer to Chapter 6.

10.4.1 Freight operators

Figure 10.2 below depicts the freight operators’ response to their individual objectives prioritized based on the cumulative points received for each objective. Percentages on top of each column show the overall mean value (all types of fleet ownerships together) for each objective. The points allocation system (as explained in Chapter 6) has two outcomes. One is to find out the ranking of given objectives by each stakeholder and the other is to find the cumulative points-based ranking. Based on the individual ranking, both cost minimization and travel time minimization received higher percentages as shown in Figure 10.3.

![Figure 0.2: Objective of freight operators](image-url)
Overall, cost minimization objective found to be the most common objective followed by the travel time minimization. Reliability is also received a reasonable level of response, but road safety has received an unexpectedly lower response rate. Reduction of externalities seems to be the least concerned objective among the freight operators, where non-of the operators have given rank one. Therefore, any new policy on improved road safety or reducing externalities has to go a long way to receive user acceptance.

### 10.4.2 Government /local authority

From the government/local authority officials, there were 16 completed responses for the question inquiring their objectives. Relevant officials (Transportation planners or traffic engineer) from Transport for Victoria, City Councils (Dandenong, Monash, Knox, Maroondah, Maribyrnong, and Casey) and Vic Roads were the main participants. The summarised responses are given in Figure 10.4.
Based on the response shown above it’s clear that the government’s main objective is to improve road safety and their least concern is about the return to road investors. Most of the other objectives received almost equal response comparatively with a slightly higher rate for reducing impacts on residents and the environment.

### 10.4.3 Residents

Question 4 of this survey, which was designed for residents or road users received about 126 responses, out of which 94 good responses were considered for analysis. The main participant for this question was members of the Maribyrnong Truck Action Group (MTAG). Since all the members in this MTAG group have a very good idea about the truck movements, it’s negative impacts and the government’s interference to their problems, I believe that better feedback was received for my survey question. Figure 10.5 depicts the summarised results based on residents/road users’ response.
Air quality has received the maximum priority (29%) among all the objectives for residents. Secondly, both less noise and improved safety were ranked with 22% each. However, it is important to highlight that residents/road users do not really pay attention to the toll charges as well as the travel times. But some concern has been shown towards congestion reduction. This again proves that car users (non-freight vehicle users) are not quite concerned about the toll levels even though the present toll charges are found to be high in Melbourne. This was the argument brought up in toll elasticity discussion where car users either have a higher willingness to pay or they are more likely to use highways, but freight vehicles do hesitate to pay extra money as high tolls.

### 10.4.4 Toll operators

There are two major toll roads in the City of Melbourne, namely, CityLink and EastLink operated by Transurban and ConnectEast respectively. Both roads were built under PPP and both roads are operating well at present condition. The survey was sent to both operating companies but both companies were refused to respond to the survey due to their data privacy policies in control. As a result, no responses were received for question 3 (in Part C) of the survey.
Therefore, to complete this section the help from a group of professionals were obtained. For the given set of objectives, a pair-wise comparison was carried out and the respective numbers were fed into the MAMCA software to obtain the final weights. The pair-wise comparison scale developed by Saaty, (2008), was used as given in Table 10.1. The agreed values for each objective by the group of professionals are given in Table 10.2.

**Table 0.1: Pair-wise Comparison Scale**

<table>
<thead>
<tr>
<th>Intensity of Importance</th>
<th>Definition</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Equal Importance</td>
<td>Two activities contribute equally to the objective</td>
</tr>
<tr>
<td>2</td>
<td>Weak or slight</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Moderate importance</td>
<td>Experience and judgement slightly favour one activity over another</td>
</tr>
<tr>
<td>4</td>
<td>Moderate plus</td>
<td>Experience and judgement strongly favour one activity over another</td>
</tr>
<tr>
<td>5</td>
<td>Strong importance</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Strong plus</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Very strong or demonstrated importance</td>
<td>An activity is favoured very strongly over another; its dominance demonstrated in practice</td>
</tr>
<tr>
<td>8</td>
<td>Very, very strong</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Extreme importance</td>
<td>The evidence favouring one activity over another is of the highest possible order of affirmation</td>
</tr>
<tr>
<td>Reciprocals of above</td>
<td>If activity (i) has one of the above non-zero numbers assigned to it when compared with activity (j), then (j) has the reciprocal value when compared with (i)</td>
<td>A reasonable assumption</td>
</tr>
<tr>
<td>1.1–1.9</td>
<td>If the activities are very close</td>
<td>May be difficult to assign the best value but when compared with other contrasting activities the size of the small numbers would not be too noticeable, yet they can still indicate the relative importance of the activities.</td>
</tr>
</tbody>
</table>

*Source: Saaty (2008)*
Table 0.2: Response from professional group

<table>
<thead>
<tr>
<th>Revenue maximisation</th>
<th>Maintaining reliability (congestion control)</th>
<th>Improved road safety</th>
<th>Minimise maintenance cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9</td>
<td>Maintain reliability (congestion control)</td>
<td>Improved road safety</td>
<td>Minimise maintenance cost</td>
</tr>
<tr>
<td>9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9</td>
<td>Improved road safety</td>
<td>Minimise maintenance cost</td>
<td>Minimise maintenance cost</td>
</tr>
<tr>
<td>9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9</td>
<td>Minimise maintenance cost</td>
<td>Minimise maintenance cost</td>
<td>Minimise maintenance cost</td>
</tr>
<tr>
<td>9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9</td>
<td>Minimise maintenance cost</td>
<td>Minimise maintenance cost</td>
<td>Minimise maintenance cost</td>
</tr>
</tbody>
</table>

10.4.5 Priorities

Based on the survey and the pair-wise comparisons used, the following weights are generated and used in this analysis. Table 0.3 depicts the final weights.

Table 0.3: Final weights obtained for various criterions

<table>
<thead>
<tr>
<th>Key Stakeholder</th>
<th>Criteria</th>
<th>Performance Measure</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freight Operators</td>
<td>User operation cost</td>
<td>User cost</td>
<td>0.3742</td>
</tr>
<tr>
<td>Freight Operators</td>
<td>Travel time</td>
<td>Total Truck Travel Time</td>
<td>0.2941</td>
</tr>
<tr>
<td>Freight Operators</td>
<td>Reliability</td>
<td>Congestion cost/ Accident cost</td>
<td>0.1723</td>
</tr>
<tr>
<td>Freight Operators</td>
<td>Road safety</td>
<td>Accident cost</td>
<td>0.1180</td>
</tr>
<tr>
<td>Freight Operators</td>
<td>Reduce externalities</td>
<td>Externalities</td>
<td>0.0414</td>
</tr>
<tr>
<td>Government</td>
<td>Congestion reduction</td>
<td>Congestion cost</td>
<td>0.1150</td>
</tr>
<tr>
<td>Local authority</td>
<td>Toll charges/Operational cost</td>
<td>0.0844</td>
<td></td>
</tr>
<tr>
<td>-----------------</td>
<td>------------------------------</td>
<td>--------</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Internal Rate of Return/ Toll Revenue</td>
<td>0.0231</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Accident cost/ Infrastructure cost</td>
<td>0.1138</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Accident cost</td>
<td>0.2849</td>
<td></td>
</tr>
<tr>
<td></td>
<td>User cost</td>
<td>0.1019</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Infrastructure cost</td>
<td>0.1156</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Externalities</td>
<td>0.1613</td>
<td></td>
</tr>
<tr>
<td>Public-Residents/Road users</td>
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</tr>
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<td></td>
<td>Road safety</td>
<td>Accident cost</td>
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</tr>
<tr>
<td></td>
<td>Less congestion</td>
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<tr>
<td></td>
<td>Less travel times</td>
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<tr>
<td></td>
<td>Toll charges for cars</td>
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<td>Toll Operators</td>
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<td></td>
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<td>Road safety</td>
<td>Accident cost</td>
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<tr>
<td></td>
<td>Impact on toll roads</td>
<td>Infrastructure cost</td>
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### 10.5 MAMCA Framework

According to Macharís et al., (2009) “The MAMCA evaluation method specifically focuses on the inclusion of qualitative as well as quantitative criteria with their relative importance, defined by the multiple stakeholders, into one comprehensive evaluation process in order to facilitate the decision making the process by the different stakeholders.” In MAMCA the following steps are followed:

**Step 1:** Problem definition and identification of alternatives

**Step 2:** Introduction of stakeholders

**Step 3:** Identification of objectives of the stakeholders define criteria and weights

**Step 4:** Assigning direct quantitative indicators for criterion

**Step 5:** Construction of an evaluation matrix
Step 6: Ranking of the various alternatives

Step 7: Actual implementation

MAMCA consists of two main phases. An analytical phase to collect all the necessary information to perform the analysis (first four steps) and a synthetic phase for the actual analysis (last three steps) (Macharis and Milan, 2015). Including stakeholders into the analysis is more time consuming and complex but it increases the likelihood of acceptance of the proposed solution significantly (Macharis, 2005). More details about the MAMCA framework can be found (Macharis et al., 2012, 2009; Macharis and Milan, 2015) or refer to Chapter 3.

Two well-known multi-criteria analysis methods developed 20 years ago, which have been extensively used for evaluation purpose are used in MAMCA (Macharis et al., 2004). The first method is known as the Preference Ranking Organization METHod for Enrichment Evaluations (PROMETHEE) and the second method is known as the Analytic Hierarchical Process (AHP) (Macharis et al., 2004). Both methods have their own strengths and weaknesses. For more details about these two methods, readers may refer to (Macharis et al., 2004). Beyond the conventional AHP method developed by Saaty, (1980), an advanced Fuzzy AHP (F-AHP) was developed later eliminating the fuzziness of the decision-makers in a stakeholder group (Aljohani and Thompson, 2018). The PROMETHEE method, which was initially developed by Brans and Vincke, (1985) and later improved by Macharis et al., (1998).

10.6 Results and Discussion

10.6.1 Mono actor analysis

The mono-actor analysis provided in the MAMCA package is useful to obtained more insightful information for the alternatives by individual stakeholder group.

10.6.1.1 Freight operators

For the freight operator stakeholder group, the highest weight was received for the user cost objective from the survey. On the other hand, the externality reduction objective
Stakeholder acceptance of optimum toll schemes

was received a very low response. Figure 10.6 depicts the result obtained from the mono-actor analysis for freight operator stakeholder group.

Out of all 10 alternatives considered in this study, the majority of the alternatives have received positive overall evaluation scores and few alternatives have ended up having overall negative evaluation scores. ‘Min user cost’, ‘min social cost’ and ‘optimum 2’ alternatives are outstanding among other alternatives by having the highest overall evaluation score. Among the six alternatives which received a positive evaluation scores, the difference in the overall score was made by the different evaluation scores received for the user cost objective. Which means evaluation scores received for travel time, reliability, road safety and reduce externalities were the same for all six alternatives. However, it is important to note that out of these six alternatives, ‘min operation cost’ alternative only has received a negative evaluation score for user cost objective while other five alternatives have received positive scores. When the real numbers are compared with other alternatives, user cost for ‘min operation cost’ alternative has a slightly positive figure even though it received a negative evaluation score from MAMCA analysis.

The ‘min environmental cost’ alternative has received only one positive score, which is for travel time and all the other scores are negative. In comparison to ‘min emission cost’ alternative ‘min environmental cost’ alternative have considered the noise cost in addition to emission cost and that has made this difference.

The ‘Typical toll’ received all negative scores on the high side and this clearly explains why the freight operators are presently not happy with the current toll charges. This could be considered as a good eye-opener for policymakers if they really consider key stakeholders when making policy decisions.

From the Freight Operators point of view, the following alternatives can be ranked as the top three options.

- Optimum 2
- Min Social Cost
- Min User Cost
10.6.1.2 Government/ Local authority

Figure 10.7 below depicts the result obtained from the mono-actor analysis for government/ local authority stakeholder group.
From the government/local authority stakeholder group, road safety criteria received outstanding weight whereas all other criterions are weighted more or less equally except return to investors. More discussion about these weights are presented in Chapter 6.

The same six alternatives, which received positive evaluation scores with respect to the freight operator’s evaluation viewpoint received positive evaluation scores from the government perspective as well. Since the government is in concern for many stakeholders involved in this problem and having conflicting objectives under their list the graph does not look very smooth compared to results obtained for other stakeholders. There is no single alternative received positive scores across all objectives and the closest one is ‘min emission cost’ alternative which received comparatively less negative value for return to investors objective while everything else is on the positive side. Once again ‘Typical toll scheme’ has received very poor feedback from the government as well but having a good positive score for returns to investors objective while having negative scores for others. As discussed in Chapter 6, return to investors is not in the priority list of the government objectives and therefore just receiving a good score in the return to investors objective only cannot make it acceptable from the overall scale.

As can be seen in the figure, ‘max. revenue’, ‘Typical toll’, ‘max. toll’ and ‘min. environmental cost’ toll schemes received overall negative scores showing that these alternatives are only good at serving investors by means of making good revenues.

Even though the overall evaluation scores are very close for five alternatives, the following three can be selected as the best alternatives from the government perspective.

- Min user cost
- Optimum 2
- Min. Emission Cost
10.6.1.3 Residents

Figure 10.8 denotes the mono-actor analysis result for resident’s stakeholder group. For resident’s air quality is the most important criteria followed by road safety, less noise, and less congestion.

![Diagram showing criteria weights and evaluation scores]

**Figure 0.8: Mono-actor analysis result for the resident’s stakeholder group**

Similar to the other two stakeholder viewpoints presented above the same six alternatives received positive evaluation scores in here as well but with the different magnitudes. Among the residents, there are few objectives that they perceive as equally important and there is no single objective is perceived as outstanding compared to others. The less noise objective has devalued many good alternatives (as perceived by other stakeholders so far) and vice versa. This is because the noise cost is measured as high when the traffic is thin compared to congested conditions and most of the high toll schemes end up with diverting more vehicles to alternative roads. This way the whole network gets more condensed and noise cost is calculated as less. For air quality, road safety, less congestion and less travel time objectives all six alternatives received the same score and thus less noise and toll charges for cars objectives are the ones which made the difference in the final evaluation score. The following three alternatives can be ranked as the best three toll schemes from the resident’s point of view.

- Optimum 1
- Min Operation cost
- Min Emission cost

### 10.6.1.4 Toll operators

Figure 10.9 denotes the mono-actor analysis result for the toll operator’s stakeholder group.

![Figure 10.9: Mono-actor analysis result for the toll operator’s stakeholder group](image)

As anyone would expect a return on investment criteria received the highest weight among the other objectives, which is about 70%. Return to investors criteria was evaluated based on the real terms but not in relative terms similar to the previous criteria evaluation. The present cost of capital in Australia, which is around 5% is set as the neutral return for the investors. From the toll operators or the investor's point of view, ‘max. toll’ scheme received the highest evaluation score followed by the ‘typical toll’. Altogether five alternatives are in favor of toll operators’ objectives with positive overall scores and five alternatives have received negative overall scores. Among the common six alternatives discussed in previous sections, five of them have received negative overall scores while one was able to move to the positive side. When we look at the five positive options for toll operators, all alternatives have received the same score for the return on investment criteria, which means, the other criterions with less
weights have decided the best among those five. Based on the overall score received, the following three alternatives can be listed as the best alternatives in terms of toll operator’s perception.

- Max Toll
- Typical Toll
- Max Revenue

### 10.6.2 Multi-actor analysis

Figure 10.10 depicts the overall result based on the evaluation carried out using MAMCA software for the given alternatives. Since stakeholder objectives are quite different and sometimes conflicting, there is no single alternative which can fit into the whole scenario perfectly. As discussed above, there are six alternatives which showed better results with three stakeholders but not with the toll operators, as can be seen in Figure 10.10. However, the ‘min operation cost’ alternative has obtained positive scores from all four stakeholders.
From the analysis, it is clear that alternatives that are well perceived by the freight operators, government and the residents are not considered as the best ones by the toll operators. The multi-actor box and Whisker analysis chart presented in Figure 10.11 clearly distinguish the well-accepted ones and the others assuming equal weights for each stakeholder group. Alternatives having mean values above the zero line can be considered as the acceptable (overall) alternatives while alternatives having mean values below the zero value are not well received by the majority of the stakeholders. Since all these alternatives are optimum toll schemes looking at one or combination of objectives they are very competitive. The variation shown in the chart would help to identify how consistent they are with given stakeholders’ objectives. For an example from the Figure 10.11 it can be seen that the ‘min operation cost’ alternative is outstanding having a higher mean value above the zero scores with less variation.

![Multi-actor box and Whisker analysis chart](image)

**Figure 0.11:** Multi-actor box and Whisker analysis chart

Similarly, the all ten alternatives considered in this analysis can be listed according to ranked considering multiple stakeholders with equal weights.

1. Min operation cost
2. Min Emissions cost
3. Optimum 1
4. Optimum 2
5. Min user cost
6. Min Social cost
7. Min Environmental cost
8. Typical toll
9. Max revenue
10. Max toll

### 10.7 Chapter summary

Stakeholder acceptance of any transport policy is crucial for its successful implementation and sustainability. There are many initiatives that have been failed in the past mostly due to stakeholder non-acceptability. Especially in urban freight transportation due to massive externalities produced by trucks and on the other hand stakeholders have become stronger and vigilant over time. As a result, the multi-stakeholder approach towards solving transportation problems is essential for sustainable transportation in the future.

This chapter focused on how different toll charging policies are perceived by various stakeholders and their level of acceptability. The toll charging policies are developed based on optimizing different objectives. Objectives include user cost, social cost, environmental cost (including emission cost) and return for the investment. One or multiple objectives were optimized, and respective toll charging schemes were found as optimal toll using a hypothetical network. These optimal solutions or toll schemes are considered as alternatives in this chapter. Even though each alternative is in favor of one or few stakeholders (objectives) the overall acceptance from all the stakeholders is questionable. Therefore, the Multi-Actor Multi-Criteria Analysis (MAMCA) methodology has been used to evaluate all alternatives and to find the best ones considering all stakeholders. In addition, for comparison purposes, few other known toll schemes are also included in the alternatives list such as ‘Typical toll scheme’. A survey was carried out to identify each stakeholder objectives and their respective weights.

Different stakeholder opinions are explicitly considered in MAMCA and have been tested and used to successfully evaluate many solutions in the past. From this study, it
was found that out of 10 alternatives 3 toll schemes are serving better for all stakeholders. Namely, ‘min operation cost’ alternative, ‘optimum 1’ alternative and the ‘optimum 2’. It is important to note that in all three solutions heavy vehicles are charged less compared to light vehicles. Another important finding from this study is that the ‘Typical Toll’ scheme, which represents the current toll charging scheme in Melbourne, has received negative feedback from most of the stakeholders.
Chapter 11

Conclusions and Future Work

11.1 Research summary

Sustainable urban goods transportation requires the development of an urban freight transport system that considers social, economic and environmental aspects. The diverse interests of various stakeholders involved in this system make it difficult to achieve such sustainable transport development. However, the complexity of issues involved can be reduced from increased awareness of stakeholders and their actions taken. Therefore, this study describes a mathematical model developed for determining optimum toll levels for freight vehicles in urban conditions considering four key stakeholders’ objectives. Three non-substitutable costs, namely, user costs (operational cost-plus toll charges), environmental costs and social costs are minimized, and Pareto optimal solutions were found using a multi-objective genetic algorithm. Lifecycle revenue from the project (IRR), which are an important factor considered by investors, were also calculated. Outcomes from a typical toll scheme (developed based on Melbourne’s CityLink network) were compared with optimal solutions and it was found
that the typical toll scheme generates more revenue at the expense of high externalities and user costs.

This study sheds light on how important the toll-setting problem is with respect to different stakeholders, due to their often-conflicting objectives. It also shows how important it is to consider network-wide effects in urban freight systems. In addition, a closer look at how each type of vehicle behaves and what impacts they may generate are essential to consider when deciding toll prices. From an investor point-of-view, the return on investment was considered when evaluating trade-offs with social and environmental costs. This understanding of a more encompassing view of the different economic, social and environmental costs are essential to make the best decision for toll charges under prevailing conditions, for example, government policies, pressure from social groups and user organizations.

The same model can be used to achieve various objectives or the policies set by the government. Emissions can be considered as a good example since emissions and air pollution from road transport are one of the major problems faced by transport authorities. This study looked at how emissions can be controlled with currently available facilities (fleets, facilities, and network) without any additional investment. Even though the government has introduced several initiatives in cities so far, these initiatives are either limited to the cordons without considering the overall network or require significant additional investment, such as changing the freight vehicle fleet to electric vehicles or building large warehouses as Urban Consolidation Centres (UCC). Therefore, the proposed method is a more effective and practical approach to reduce roadside emissions.

In addition, revenue generated from the toll roads is also considered to be retained by investors in the long run. Therefore, multi-class toll charges were used as the decision-making variables and the most common toll charging schemes were analyzed with respect to possible outcomes in terms of revenue, overall emissions, total road user operation costs, and total travel times. The application of proposed toll charging scheme was investigated via a hypothetical road network and a real-world network and compared with popular schemes including the present scheme (i.e. ‘Typical Toll’
scheme) in Melbourne, Australia. Genetic algorithms were used to identify optimal solutions.

The results show that compared to the ‘Typical Toll’ scheme, the proposed method (Link Toll) was able to reduce emission costs by 8.2% and 12.8% respectively from the hypothetical network and from the real network, respectively. Although there is a loss of revenue in the proposed minimum emission schemes compared to the typical toll scheme in both cases, when considering other factors, such as operation costs, total travel time, etc., the proposed scheme leads to more qualitative savings. These saving from operation cost and total travel time are in the interest of other stakeholders, including freight users, which is also important to consider when it comes to real applications. In addition, this study has demonstrated that some currently used toll schemes result in large emissions and other negative impacts, such as high operation cost and high total travel time. Therefore, this study has provided insights into all aspects of the impacts generated from city logistics, including economic, environmental and social impacts.

The methodology developed in this study illustrates that improved environmental outcomes can be obtained by adjusting toll levels and this requires less additional investment in infrastructure. The method can be applied to any road network with toll roads to reduce emissions from road transport as a simple, yet a sustainable solution for protecting all key stakeholders. Other positive policies, for example promoting lower emission vehicles and electric vehicles, would be an added advantage to minimize network-based emissions.

In the case of urban toll roads, the toll price decision is not limited to the investor and administrators anymore where any user acceptable toll structures can be implemented. The public is more concern about environmental and social costs (externalities) than ever and as a result, more stakeholder perspectives need to be considered when deciding toll levels. Therefore, this study also looked at identifying major stakeholder concerns and how equilibrium solutions can be achieved. From this study, it can be concluded that each stakeholder objective is conflicting with each other and there is no single optimum solution available which can satisfy all stakeholders. As a result, after
demonstrating various scenarios a few cases were selected as fair decisions. Furthermore, a policy decision about not only the toll itself but how subsidies can help to obtain better results when the overall situation is considered was demonstrated.

The current toll charges on EastLink and CityLink found to be high for all types of vehicle classes compared to the damage they cause to pavements as well as externalities. In addition, it was proven that higher toll charges, especially for heavy vehicles, generate more externalities when an entire network is considered, and most toll schemes were found to be non-optimal solutions where the negative impacts have possibly been neglected.

This model clearly shows that increasing toll revenues does not always produce higher revenue. Given the diverse interests of stakeholders, there is no single optimal toll that can maximize benefits for all stakeholders. However, if trade-offs are properly considered sub-optimal solutions can be found which all parties can reasonably agree. This study has given a more encompassing view on multi-class toll charges and respective toll revenues and other negative impacts. If investors are required to make higher returns out of infrastructure projects (like PPP) for their survival, it is better to consider toll subsidies rather than charging high tolls for road users, especially for large trucks. This model allows the decision maker to be aware of the consequences arising from toll schemes and identification of the most efficient toll schemes a government should consider.

In summary, this study has shed the light on two main points: firstly, finding optimal toll charges in order to achieve a given revenue at the expense of minimal costs (externalities and operation costs), which decision makers should try to avoid. Secondly, how subsidies can be effectively used to satisfy investors while reducing externalities and operation costs.

Finally, understanding the key stakeholders and their requirements is critical for improving the sustainability of transport systems and increasing the acceptability of any toll policy. Thus, MAMCA has used to evaluate the optimum solution among alternatives.
From the MAMCA analysis, the best toll scheme out of the optimum solutions given by the mathematical model considering stakeholder acceptability was found. It can be concluded that optimal solutions obtained from the Pareto-optimal curve are the best toll schemes considering multi-stakeholder acceptability for sustainable City Logistics. Thus, policymakers can now easily select one of the best solutions considering the given circumstances without worrying about the toll schemes acceptance or sustainability in the future.

11.2 Applications and usage

Since this study looked at multi-stakeholder optimisation, the value and the significance of the research study presented in this thesis can be expressed as applications and usage of this study for each stakeholder.

11.2.1 Government (and Public)

- The model developed can be used by the government to estimate externalities produce by different heavy vehicle classes in response to various toll levels
- Thus, this model will enable the government to negotiate (with facts) with toll operators deciding the toll levels based on social and environmental costs and further can use as an input to a new policy decision such as shadow toll
- Further, this research study will enable the government to understand the behaviour of freight vehicles, including response to toll charges, and this information can be used to shape the behaviour of freight movement to form more sustainable freight movement system in urban conditions in the future.

**Examples**

1. Based on this model output the government can decide which heavy vehicle types to encourage in the future to minimise total cost of city logistics considering the demand conditions
2. If the government decided to pay subsidies to receivers to achieve a more sustainable system, this model will help to decide the price levels
Conclusions and future works

- Can use this model as a tool to estimate total outcome if the government is willing to introduce any sort of road user charging mechanism to control traffic or emissions in the future.

11.2.2 Toll Road operators

- The model developed will help toll road operators understand the trade-offs between toll levels and externalities produced by heavy vehicles in response to such surcharges. Therefore, they will be more aware of the conditions when negotiating with governments.
- Thus, this model can be used to decide more appropriate toll charges for different heavy vehicle classes (considering the efficiency of truck, damages to pavement, space taken), more effective time of day (TOD) pricing which enables them to recover infrastructure costs more effectively while optimising their profits.
- When toll operators use toll charges as a congestion management toll for heavy vehicles this model will give them the exact outcome from their decisions.

11.2.3 Trucking companies

- The model provides guidance for trucking companies to minimise their overall operating cost. This includes route choice, time of travel and depot selection.
- Fleet size and ownership are key parameters shaping the behaviour of trucking companies. Thus, this model enables them to understand what vehicle fleet types are required to minimise their cost of operation (toll is part of it) for given delivery types and the efficient heavy vehicles types should be used in the long run. (ex: B doubles)
- This model can be used as an insight to shape company policies (for large companies) for the more suitable transport system.
- This model will also make small trucking companies (market share is larger than what we think) understand the consequences of route choice and toll charges.
- This research study will enable us to understand the behavioural differences between large to small trucking companies providing transport and ancillary
services, which is necessary to improve the sustainability of the urban freight movement.

11.2.4 Others users

- Freight forwarders can use this model to optimise their transportation costs by virtue of selecting appropriate locations for warehouses and depots.

11.3 Limitations and future work

There are certain assumptions and estimates made in this research study, mostly in the sub-models developed, which can be improved in the future.

- Real data pertaining to operation and maintenance costs of toll roads could be collected which would help to model more appropriate toll charges (investment recovery) for freight vehicles.

- At the same time more accurate estimates on VOC, VOT, EC, and SC are encouraged to estimate truck costs in Australia because some values used in this study are based in different countries (mostly Europe) which may differ from the local conditions.

- Extensive DC surveys can be carried out for different vehicles classes, transporting various goods in order to obtain more precise toll resistance curves.

- Surveys for the MAMCA could be extended over more participants covering many clusters of stakeholders to improve the quality of the study.

Apart from the improvements from data, some future directions for this study are suggested as follows:

- At the end of the day, it’s the transport planner’s responsibility to minimize the overall cost of freight transportation, not individual costs, and thus the analysis
can be extended to model the pavement damage caused by freight vehicles to
determine more appropriate toll charge and more emphasis should be given to
externalities produced by freight vehicles when using different road types. In the
future, the Internet of Things (IoT) could be applied to collect more information
to develop and apply a more sophisticated pricing model considering many
parameters.

- In future research, apart from the distance based fixed toll charging scheme,
different toll charging schemes such as link based, cordon based or gross vehicle
mass (GVM) based (multi-class, load based) schemes could be applied and their
impacts should be assessed.

- Future work could look at better ways to combine individual externalities, since
converting all into dollar terms and summing up using the same weight (as one)
is not well accepted.

- In the future, this method could be extended and applied to investigate the
effects of road pricing to minimize emissions (or any other cost element) when
vehicles are charged for using all links in the network. This could be aimed at
replacing fuel taxes and other forms of traditional non-usage-based road
charging systems.

- It is recommended to carry out the MAMCA analysis for a selected number of
alternatives, probably the second group of alternatives (considering this analysis
as a screening step) in order to see more distinct differences between solutions
with respect to multiple stakeholders and criterion.
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Appendix

Appendix 3a: Parameters used in the hypothetical network

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Notes: All links are two directional with same capacity and distance
Alpha and beta values are considered as 0.15 and 4 respectively for all links
Road type 1,2,3 refers to freeway, highway and other roads respectively

Appendix 3b: OD matrix- total vehicle demand (veh/hour)

<table>
<thead>
<tr>
<th>O/D</th>
<th>1</th>
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<th>3</th>
<th>4</th>
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<th>6</th>
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<td>1,500</td>
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</tbody>
</table>

Note: total demand consists of 50% cars, 25% 2 axle trucks, 15% 4-axle trucks and 10% 6 axle trucks for all OD pairs
### Freight Transportation in Urban Cities: Questionnaire

**Part A - For Fleet/Freight Operators**

1) Ownership of the fleet

- [ ] Owner Driver (or employee)
- [ ] For-hire (company)
- [ ] Both

1a) If both, for-hire percentage is

- [ ] Less than 10%
- [ ] Less than 40%
- [ ] Less than 80%
- [ ] Above 80%

2) Vehicle fleet details

<table>
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<tr>
<th>Number of Trucks</th>
<th>Short</th>
<th>2 Axle</th>
<th>3 Axle</th>
<th>4 Axle</th>
<th>3 Axle Articulated</th>
<th>4 Axle Articulated</th>
<th>5 Axle Articulated</th>
<th>6 Axle Articulated</th>
<th>8 Doubles</th>
<th>Road Train</th>
</tr>
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<tr>
<td>2-5 Trucks</td>
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<td>6-10 Trucks</td>
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</thead>
<tbody>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Food (Non-refrigerated)</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>General Freight</td>
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<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Construction or Raw Materials</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Petroleum/Chemical Products/Liquids</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td>Other Manufactured Products</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other Commodity</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3) What objectives do you have as a freight operator in your day-to-day travel? (give points out of 100)

- [ ] Cost minimisation
- [ ] Improved road safety
- [ ] Travel time minimisation
- [ ] Reduce externalities*
- [ ] Reliability

*Externalities: Emissions, Noise
4) Who does the route selection? (give points out of 100)

- Driver
- Company/Manager
- Software (dedicated service)
- Historical/ Traditional/ Always
- Readymade Software (ex: Google Maps)
- Other

5) What factors do you consider when deciding routes? (give points out of 100)

- Distance
- Commodity Type/ Loading
- Vehicle Operation Cost
- Delivery/ Departure Time
- Toll Charge
- Road Type/ Turning Restrictions/ Road Curfew
- Reliability
- Externalities Produced*

*Externalities: Emissions, Noise, Congestion, Safety

6) When do you use toll roads? (give points out of 100)

- When customer requested
- During congested times
- When truck is Loaded
- Never
- Always
- During night times
- When route is given

7) What strategies do you use to avoid congested periods (give points out of 100)

- Shift to off-hour deliveries
- Change starting time
- Use toll roads
- Nothing
- Load sharing
- Use consolidation centres
- Change delivery time

8) Who decides the delivery time? (give points out of 100)

- Driver
- Company/Manager
- Receiver/ Sender
- Other
### Appendix 6b: Part B

**Block I**

**Freight Transportation in Urban Cities: Questionnaire**

**Part B - For Freight Operators (or Drivers)**

<table>
<thead>
<tr>
<th>Select Vehicle Type</th>
<th>Select Commodity Type</th>
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<td>Short</td>
<td>Food (Refrigerated)</td>
</tr>
<tr>
<td>2 Axle</td>
<td>Food (Non-refrigerated)</td>
</tr>
<tr>
<td>3 Axle</td>
<td>General Freight</td>
</tr>
<tr>
<td>4 Axle</td>
<td>Construction or Raw Materials</td>
</tr>
<tr>
<td>3 Axle Articulated</td>
<td>Petroleum/Chemical</td>
</tr>
<tr>
<td>4 Axle Articulated</td>
<td>Products/Liquids</td>
</tr>
<tr>
<td>5 Axle Articulated</td>
<td>Other Manufactured Products</td>
</tr>
<tr>
<td>6 Axle Articulated</td>
<td>Waste</td>
</tr>
<tr>
<td>B-Doubles</td>
<td>Other Commodity</td>
</tr>
<tr>
<td>Road Train</td>
<td></td>
</tr>
</tbody>
</table>

*Please choose one option from each choice set given below considering trip starting time is between [3-11 AM, 11-4 PM, 4-9 PM, 9 PM-3 AM].*

#### CHOICE SET 1

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Highway</th>
<th>Toll Option A</th>
<th>Toll Option B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Travel Time</td>
<td>12 Min</td>
<td>7 Min</td>
<td>10 Min</td>
</tr>
<tr>
<td>Toll Charge</td>
<td>$0</td>
<td>$5</td>
<td>$6</td>
</tr>
<tr>
<td>Travel Distance</td>
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<td>12 Km</td>
<td>7 Km</td>
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#### CHOICE SET 2

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<th>Toll Option B</th>
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</thead>
<tbody>
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<td>Travel Time</td>
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<td>5 Min</td>
<td>5 Min</td>
</tr>
<tr>
<td>Toll Charge</td>
<td>$0</td>
<td>$3</td>
<td>$10</td>
</tr>
<tr>
<td>Travel Distance</td>
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<td>14 Km</td>
<td>10 Km</td>
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#### CHOICE SET 3

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<th>Toll Option B</th>
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<td>Travel Time</td>
<td>12 Min</td>
<td>7 Min</td>
<td>5 Min</td>
</tr>
<tr>
<td>Toll Charge</td>
<td>$0</td>
<td>$8</td>
<td>$3</td>
</tr>
<tr>
<td>Travel Distance</td>
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#### CHOICE SET 4

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<tbody>
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<td>Travel Time</td>
<td>10 Min</td>
<td>10 Min</td>
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<tr>
<td>Toll Charge</td>
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<td>$10</td>
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<tr>
<td>Travel Distance</td>
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### Appendix

#### CHOICE SET 5

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<th>Toll Option B</th>
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<tr>
<td>Toll Charge</td>
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<td>$5</td>
</tr>
<tr>
<td>Travel Distance</td>
<td>12 Km</td>
<td>7 Km</td>
<td>14 Km</td>
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</tr>
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<td>$3</td>
</tr>
<tr>
<td>Travel Distance</td>
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<td>7 Km</td>
<td>12 Km</td>
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#### CHOICE SET 7

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</thead>
<tbody>
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<td>12 Min</td>
</tr>
<tr>
<td>Toll Charge</td>
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<td>$10</td>
<td>$5</td>
</tr>
<tr>
<td>Travel Distance</td>
<td>14 Km</td>
<td>7 Km</td>
<td>12 Km</td>
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#### CHOICE SET 8

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</thead>
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<td>$5</td>
<td>$3</td>
</tr>
<tr>
<td>Travel Distance</td>
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<td>7 Km</td>
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<td>Options</td>
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### Freight Transportation in Urban Cities: Questionnaire

**Part B - For Freight Operators (or Drivers)**

<table>
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<th>Select Vehicle Type</th>
<th>Select Commodity Type</th>
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<td>Short</td>
<td>Food (Refrigerated)</td>
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<td>Food (Non-refrigerated)</td>
</tr>
<tr>
<td>3 Axle</td>
<td>General Freight</td>
</tr>
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<td>4 Axle</td>
<td>Construction or Raw Materials</td>
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<tr>
<td>3 Axle Articulated</td>
<td>Petroleum/Chemical Products/Liquids</td>
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<td>Other Manufactured Products</td>
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<td>6 Axle Articulated</td>
<td>Other Commodity</td>
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<tr>
<td>B-Doubles</td>
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<tr>
<td>Road Train</td>
<td></td>
</tr>
</tbody>
</table>

*Please choose one option from each choice set given below considering trip starting time is between [3-11 AM, 11-4 PM, 4-9 PM, 9 PM-3 AM].*

**CHOICE SET 1**

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Highway</th>
<th>Toll Option A</th>
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**CHOICE SET 2**

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**CHOICE SET 3**

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**CHOICE SET 4**

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### Appendix

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<th>Highway</th>
<th>Toll Option A</th>
<th>Toll Option B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Travel Time</td>
<td>5 Min</td>
<td>7 Min</td>
<td>5 Min</td>
<td></td>
</tr>
<tr>
<td>Toll Charge</td>
<td>$0</td>
<td>$10</td>
<td>$5</td>
<td></td>
</tr>
<tr>
<td>Travel Distance</td>
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<td>10 Km</td>
<td>7 Km</td>
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<td>5 Min</td>
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<tr>
<td>Toll Charge</td>
<td>$0</td>
<td>$3</td>
<td>$10</td>
<td></td>
</tr>
<tr>
<td>Travel Distance</td>
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<td>10 Km</td>
<td>10 Km</td>
<td></td>
</tr>
<tr>
<td>Options</td>
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<td>Travel Time</td>
<td>10 Min</td>
<td>7 Min</td>
<td>12 Min</td>
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<tr>
<td>Toll Charge</td>
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<td>$8</td>
<td>$5</td>
<td></td>
</tr>
<tr>
<td>Travel Distance</td>
<td>14 Km</td>
<td>10 Km</td>
<td>14 Km</td>
<td></td>
</tr>
<tr>
<td>Options</td>
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<table>
<thead>
<tr>
<th>CHOICE SET 8</th>
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<th>Toll Option A</th>
<th>Toll Option B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Travel Time</td>
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<td>10 Min</td>
<td>5 Min</td>
<td></td>
</tr>
<tr>
<td>Toll Charge</td>
<td>$0</td>
<td>$5</td>
<td>$10</td>
<td></td>
</tr>
<tr>
<td>Travel Distance</td>
<td>12 Km</td>
<td>12 Km</td>
<td>10 Km</td>
<td></td>
</tr>
<tr>
<td>Options</td>
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</tbody>
</table>
Appendix 6c

Freight Transportation in Urban Cities: Questionnaire

Part C: For Government Officials, Toll Operators and Residents/Road users (non-freight)

1) Select the category you belong to

- Government/Local Authority
- Toll Operator
- Resident
- Road User

**Government or local authority** representative please answer **Question 2 only**.

**Toll operator** representative please answer **Question 3 only**.

**Residents or road users**, please answer **Question 4 only**.

2) What objectives do you have when managing (making strategic plans) freight transportation? (give points out of 100)

- Congestion control
- Network usage optimisation
- Sustainability
- Road safety
- Return to road investors (toll roads)
- Reduction of road maintenance cost
- Reduction of freight users operation cost
- Reduce impact on residents and environment

3) What objectives do you have when operating a toll road? (give points out of 100)

- Revenue maximisation
- Improved road safety
- Maintain Reliability (Congestion control)
- Minimise maintenance cost

4) What objectives do you want to achieve regarding road/freight transportation? (give points out of 100)

- Improved air quality
- Less congestion
- Less noise
- Less travel times
- Improved road safety
- Less toll charges
Plain Language Statement

Melbourne School of Engineering/Department of Infrastructure Engineering/Faculty of Engineering

Project: Freight Transportation in Urban Cities

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Tel: +61 356439 Email: rpthom@student.unimelb.edu.au
Mr. Loshaka Perera (Ph.D. student) Email: hewagep@unimelb.edu.au

Introduction
Thank you for your interest in participating in this research project. The following few pages will provide you with further information about the project, so that you can decide if you would like to take part in this research.

Please take the time to read this information carefully. You may ask questions about anything you don’t understand or want to know more about.

Your participation is voluntary. If you don’t wish to take part, you don’t have to. If you begin participating, you can also stop at any time.

What is this research about?
This research has three parts. Part A and Part B of this survey investigates the decision-making behaviour of Victorian freight vehicles, specially how freight vehicles respond to toll levels in urban conditions. Part C of the survey investigates the importance of different objectives for stakeholders. The outcome of this survey will be used to model urban freight movements considering economic, environmental and social factors and to investigate more sustainable toll schemes.

What will I be asked to do?
Should you agree to participate you will be given a short-printed questionnaire. If you are a freight operator you will be given a questionnaire with two parts (Part A and B) or else you will be given only Part C of the questionnaire. Part A of the questionnaire has several general questions about what you transport and what parameters you consider when you make day-to-day decisions (e.g. route selection). Part B will give you several scenarios, to choose one out of two options given for each scenario based on your perception (see the example given below). To answer all the questions given in both Part A and B of this survey will take approximately 15-20 minutes. Part C of the questionnaire is for other stakeholders [other than freight operators] and some of your objectives are listed in the given form. You are supposed to assign points out of 100 to listed objectives considering their importance to sustainable freight transportation. This should take less than 5 minutes.

Example of a Scenario (from Part B):

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Highway</th>
<th>Toll Option A</th>
<th>Toll Option B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Travel Time</td>
<td>12 Min</td>
<td>7 Min</td>
<td>10 Min</td>
</tr>
<tr>
<td>Toll Charge</td>
<td>50</td>
<td>55</td>
<td>58</td>
</tr>
<tr>
<td>Travel Distance</td>
<td>14 Km</td>
<td>12 Km</td>
<td>7 Km</td>
</tr>
</tbody>
</table>

Ethics ID Number: 1851746.1
What are the possible benefits?
This survey will act as an input to a main study which will be looking at how toll levels can be optimised considering multi-stakeholder, multi-class conditions based on not only economic, but also social and environmental factors. Therefore, this will benefit all stakeholders in the long run. Reduction of social and environmental costs will be the major benefits from this research.

What are the possible risks?
There are no possible risks from participation or non-participation in this survey because the survey has no intention to collect any sensitive data which may create such risks. According to non-sharing policy of the University any individual data collected will not be shared with any party other than the research team. This will ensure minimum risk for participants with respect to information provided in the survey.

Do I have to take part?
No. Participation is completely voluntary. You can withdraw at any time, even if you are half-way through. If you chose to withdraw from this study, all your data will be destroyed.

Will I hear about the results of this project?
The results will be published in journal articles, conference papers and final thesis. Apart from that, the results will be electronically sent to any participant up on their request.

What will happen to information about me?
According to University procedures the data gathered by this project will be retained for five years after the date of the last publication which includes the results. Data will be destroyed after this period and no one else can possibly access the data other than the project team during this time.

Where can I get further information?
If you would like more information about the project, please contact the researchers; A/P Russell G. Thompson [Tel: +61 356439 Email: rythom@unimelb.edu.au], or Loshaka Perera [Tel: 0452 55 674 Email: hewagep@student.unimelb.edu.au].

Who can I contact if I have any concerns about the project?
This research project has been approved by the Human Research Ethics Committee of The University of Melbourne. If you have any concerns or complaints about the conduct of this research project, which you do not wish to discuss with the research team, you should contact the Manager, Human Research Ethics, Research Ethics and Integrity, University of Melbourne, VIC 3010. Tel: +61 3 8344 2073 or Email: HumanEthics-complaints@unimelb.edu.au. All complaints will be treated confidentially. In any correspondence please provide the name of the research team or the name or ethics ID number of the research project.
### Appendix 8a: Link wise toll schemes for the two optimal schemes under the link toll scenario

<table>
<thead>
<tr>
<th>Link #</th>
<th>Toll Charge (A$/km) for Min. Emissions</th>
<th>Toll Charge (A$/km) for Max. Revenue</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Car</td>
<td>2 Axle</td>
</tr>
<tr>
<td>108</td>
<td>0.11</td>
<td>0.91</td>
</tr>
<tr>
<td>103</td>
<td>0.16</td>
<td>0.59</td>
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<tr>
<td>114</td>
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<td>1108</td>
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<tr>
<td>1103</td>
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<td>1114</td>
<td>0.45</td>
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</table>

*Note: Link numbers shown in Figure 1 denotes the flow from West-East direction, while the same number in thousands denotes the opposite directional flow*
Appendix 10a: Values obtained from the model for various alternatives considered in MAMCA analysis

<table>
<thead>
<tr>
<th>Performance Measure</th>
<th>Alternative</th>
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<td>Description</td>
<td>Abbreviation</td>
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<td>Toll (cars)</td>
<td>Toll_C</td>
</tr>
<tr>
<td>Toll (2 axle)</td>
<td>Toll_2</td>
</tr>
<tr>
<td>Toll (4 axle)</td>
<td>Toll_4</td>
</tr>
<tr>
<td>Toll (6 axle)</td>
<td>Toll_6</td>
</tr>
<tr>
<td>Emission cost</td>
<td>EmC</td>
</tr>
<tr>
<td>Noise cost</td>
<td>NoC</td>
</tr>
<tr>
<td>Accident cost</td>
<td>AcC</td>
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<tr>
<td>Accident cost (toll rds)</td>
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<tr>
<td>Congestion cost</td>
<td>CnC</td>
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<td>Congestion cost (toll rds)</td>
<td>CnC_T</td>
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<tr>
<td>Infrastructure cost (other rds)</td>
<td>InC_nT</td>
</tr>
<tr>
<td>Infrastructure cost (toll rds)</td>
<td>InC_T</td>
</tr>
<tr>
<td>Externalities</td>
<td>Ext [EnC+SoC]</td>
</tr>
<tr>
<td>User cost</td>
<td>UsC</td>
</tr>
<tr>
<td>Operation Cost</td>
<td>OpC</td>
</tr>
<tr>
<td>Toll Revenue</td>
<td>Toll Rev</td>
</tr>
<tr>
<td>Internal Rate of Return</td>
<td>IRR (%)</td>
</tr>
<tr>
<td>Total Travel Time</td>
<td>Tot TT</td>
</tr>
<tr>
<td>Total Truck Travel Time</td>
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</tbody>
</table>