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Optimal toll charges for multi-class vehicles in City Logistics

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Abstract

Many expressway facilities around the world are built using public-private partnerships (PPP), which is a popular method to finance urban roads. Various toll charges are imposed over multi-class vehicles by road investors in association with the government to recover and produce a return on their investment. High toll charges on heavy vehicles can lead to heavy vehicles using alternate roads to reduce freight costs. The resulting increase in the use of substandard roads by heavy vehicles, which has led to higher environmental and social costs, i.e. the externalities. Presently, externalities are paid by the general public (indirectly) and this has become a major problem in many cities, including the Melbourne. As a result of increasing externalities, there is a growing demand for road users to pay for these externalities, to stop cross subsidization of transport externalities.

In this study, we propose an innovative approach to reduce the total cost, including economic, social and environmental costs, of goods movement within cities via charging optimal tolls for expressway facilities. This approach looks at the optimization of multi-objectives from multi-stakeholders under a bi-level modelling framework. Advanced version of Genetic Algorithm was used to find the optimal set of solutions, which shows the trade-offs between different objectives. The benefits of this approach are demonstrated using a hypothetical network with static demand conditions. Solutions with different economic, social and environmental cost combinations were obtained considering different stakeholders' preferences. This study provides insights into how sensitive the toll price setting can be and how a win-win solution can be achieved.

Keywords: Urban freight, Optimum toll levels, City logistics, NSGA II

1.Introduction

In the domain of City Logistics, much research has been carried out to find solutions for urban freight transport issues, optimizing the total cost with the support of advanced information systems (Taniguchi and Thompson, 2014). Various stakeholders in urban freight systems have different goals and objectives which may conflict with one another (Perera and Thompson, 2020). As a result, integrating various objectives and providing solutions to all stakeholders has become one of the greatest challenges in modelling urban freight activities (Tamagawa, Taniguchi and Yamada, 2010). At present, mobility, sustainability, liveability, and resilience are key objectives considered under City Logistics (Taniguchi and Thompson, 2014). The mobility aspect looks at the reliability of trips made by trucks which can be measured in terms of travel times. Lesser travel times means less congestion and thus, mobility aspect covers the congestion as well. In contrast, the sustainability aspect is focused on producing less environmental impacts and fair usage-based costing mechanism. In other words, most infrastructure costs are being recovered by authorities in terms of indirect methods, such as fuel taxes or registration fees. With modern changes in technology such revenues have declined (less fuel consumption due to efficiency improvement in vehicles and also increase in usage of electric vehicles) with authorities failing to recover the full cost of infrastructure maintenance (Perera and Thompson, 2020). As a result, infrastructure maintenance costs have ultimately become a social cost which deplete the general taxes of the population, sometimes from the people who are not even involved in the transport operation. The livability aspect is more concerned about road safety (crash reduction) and healthy living (less emissions and noise). Resilience is a new aspect which considers efficient and agile operations of humanitarian logistics after disasters (natural or manmade). Therefore, City Logistics mainly considers mobility, sustainability and livability objectives in day to day operations. In other words, these objectives can be interpreted in terms of cost drivers, namely economic, social and environmental costs.

Environmental costs mainly consist of emissions and noise costs and the social costs are mainly considered as congestion, crash and infrastructure costs. Road transportation has been found to be a major source of air pollution (Caiazzo et al., 2013; Chen and Yang, 2012; Dedoussi and Barrett, 2014; Galgamuwa, Perera and Bandara, 2016b, 2016a) and around 20% of the population in European Union are exposed to environmental noise levels which have been considered as unacceptable by health experts (Day, Bateman and Lake, 2006). It is clear from past studies that trucks impose large negative impacts on the environment compared to light vehicles (Tamagawa, Taniguchi and Yamada, 2010). At the same time, deaths from road crashes remain at about 1.2 million per annum globally (Devasurendra, Perera and Bandara, 2017) and the estimated economic cost of crashes in Australia was estimated to be 17 billion AUD in 2003 (Connelly and Supangan, 2006). Congestion, measured in terms of delays for trucks have exceeded $7.8 billion a year (Kawamura and Rashidi, 2010) and billions of dollars were spent on infrastructure maintenance and developments through central budgets (BITRE, 2011). Economic costs of freight transportation may include direct vehicle operating costs in terms of fuel, maintenance, wear and tear, and so on plus wages for drivers. Since the externalities are also part of the transportation, stakeholders now demand such externalities to be included in the real transportation costs. This will help road users (e.g. freight operators) calculate their true cost and charge the receivers accordingly rather transferring externality costs to society. When roads are built using private money, the public is more concerned about bearing externalities because these projects are being carried out for making profit and in such circumstances all negative outcomes from the project itself have to be absorbed by the project.

With the rising demand for transportation, private-public-partnership (PPP) projects to build road infrastructure have become common throughout the world. As a result, toll charges are placed on vehicles using such facilities for investment recovery. Therefore, the application of various toll charging schemes by investors is inevitable. Recent studies have found that toll charges on freight vehicles are high in many facilities all over the world and disparity exists between classes of vehicles (Holguín-Veras, Cetin and Xia, 2006; Holguín-Veras and Cetin, 2009; Perera, Thompson and Yang, 2016). This has resulted in the common toll avoidance practice by heavy vehicles all over the world (Chen, Perera and Thompson, 2018; McKinnon, 2006; Quak and van Duin, 2010; Yang et al., 2002) and the consequences are not trivial. When heavy vehicles divert from high quality roads to sub-standard roads (i.e. from freeways to arterials) to avoid tolls, more externalities are produced compared to light vehicles (Cruz et al., 2012; Perera, Thompson and Wu, 2020; Swan and Belzer, 2010) creating greater impacts on residents.

In the present context, City Logistics research involves developing innovative approaches for reducing the total cost, including economic, social and environmental costs of goods movement within cities (Taniguchi and Thompson, 2002). Therefore, this study looks at how tolls can be used to improve the efficiency of City Logistics. Since City Logistics aims for total system optimization, multiple-objectives and the behaviour of multiple-stakeholders need to be taken into account (Perera and Thompson, 2020). Therefore, toll charges are considered in this study as the key decision variables while optimizing total costs considered in City Logistics.

The rest of the paper is organized as follows. The next section describes the methodical framework with bi-level modelling. A case study is presented in Section 3 and in Section 4 the results are discussed. Finally, conclusions are made with recommendations for future work.

2. Methodology

The toll setting problem is a bi-level problem where investors in collaboration with the government set toll prices (on certain links) with the intention of optimizing intended objectives as depicted in Figure 1.

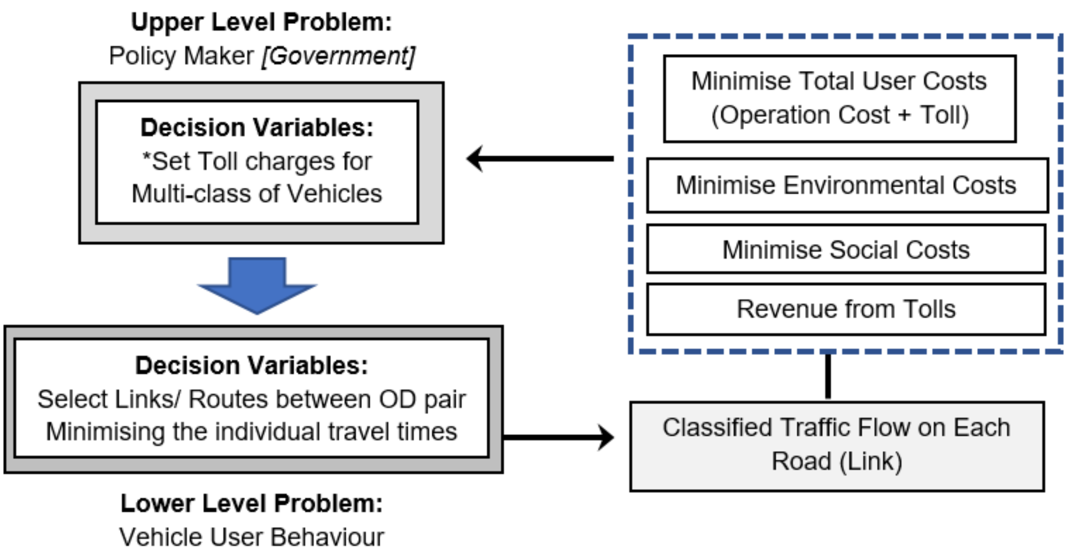


Figure 1: Bi-level problem structure

Once the prices are set, users react by setting up their itinerary such that their total travel costs, i.e. standard operating costs (time, distance, etc.) plus tolls, are minimized. This hierarchical relationship exists between two autonomous, possibly conflicting decision makers. However, it is important to note that leaders cannot control the 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 the users' decision to choose which route should be taken to a given destination. Thus, the model developed has two levels of decision making, government at the upper-level and road users at the lower-level. More information about bi-level model for toll setting problem can be found in the study by Perera, Thompson and Wu (2021).

2.1. Upper-level model

As the upper level decision maker, the government has to set the toll price for (road investors need permission from the government to set toll charges) vehicles on toll roads. Despite producing a decent return for the road investors (otherwise PPP will fail) it is the government's responsibility to safeguard the other stakeholders such as road users and the general public as well. Therefore, the government objectives can be broadly classified into two objectives as depicted below.

Objective 1: Minimization of Total Cost

$$\min Total\ Costs\ (TC) = Externalities + User\ Costs$$
$$\text{Externalitites} = \ = Environmental\ Costs + Social\ Costs$$
$$\text{Environmental Costs} = emisions\ cost + noise\ costs$$
$$\text{Social Costs} = crash\ costs + congestion\ costs\ + infrastructure\ costs$$
$$\text{User Costs} = Operation\ costs + Toll\ charges$$

$$\min \text{TC} = \sum_{a\in A\cup\overline{A}} \sum_{m\in M} \{ [\alpha EM_a^m + \beta NC_a^m + \gamma AC_a^m + \theta CC_a^m + \vartheta IC_a^m] * d_a * x_a^m + [VC_a^m d_a + VT^m t_a] * x_a^m + T_a^m * x_a^m \} \quad (1)$$

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)
VC_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 (refers to the damage caused by each vehicle) 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 ratio), $a \in A \cup \overline{A}, m \in M$ (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)
α, β : Weights at which environmental costs are implied (all assumed as 1)
$\gamma, \theta, \vartheta$: Weights at which social costs are implied (all assumed as 1)

Equation (1) denotes the first objective function for upper-level, which looks at the total cost (including externalities) of freight transportation. In City Logistics research it is believed that since externalities are produced as a part of the urban freight system, freight vehicles need to bear these costs as well (Taniguchi and Thompson, 2014). Otherwise these externalities will be borne by the general public, which is also a concern for the government. As a result, externalities are considered under the total cost for freight users. In economic theory, toll charges are considered as a transfer price, but not as a direct cost. However, toll charges can be considered as a direct cost for users in this context because the toll charge is a cost for users to determine their trips/routes. Thus, toll charges are added to the total cost of users. Revenue from tolls is considered as an objective of the upper-level decision maker, which is the government. Therefore, the first objective considered in the upper-level is minimization of total cost and the second objective is to provide a decent return to the road investors.

Externalities (emissions, noise, crash, infrastructure and congestion) are measured in the Australian context based on available data or otherwise directly extracted from literature after conversion. The methods and calculations can be found in Perera and Thompson, (2020) and Yang et al., (2016).

Objective 2: Decent Return to Road Investors from Toll Charges

In the second objective, revenue from toll charges alone doesn't make a sense since the road investors are looking at overall costs and benefits from the project. In other words, investors in a PPP are more concerned about the net profit generated from the project but not the toll charges or revenue from different vehicle types. Thus, the number of operational years given for the investor is another critical parameter when deciding toll charges (Odeck, 2017). Therefore, the costs and benefits for the life cycle of the project have been considered here in order to arrive at an acceptable return. The mathematical formulation shown below (equation 2) considers the life cycle costs and benefits of the infrastructure development and used to calculate the break-even return on the investment known as the Internal Rate of Return (IRR) that is calculated as the rate at which the net present toll revenue (NPTR) is equal to zero. The IRR is one of the top project evaluation criteria not only in Australia but also in many countries of the world (Truong, Partington and Peat, 2008). In this calculation it is assumed that, $FM_a(C_a) = \lambda\, ICC_a(C_a)$, where $0 < \lambda \leq 1$. This implies that the fixed maintenance cost per year is considered as a fixed percentage of the capital cost of the infrastructure. Here, λ is assumed to be 0.05. It was assumed that toll roads operate for 24 hours a day where peak hour volumes are equal to 10% of AADT (Average Annual Daily Traffic). The term d_t is used to convert the peak hour revenue to yearly revenue from toll charges after deducting the infrastructure damage costs due to each vehicle type. Capital costs of the infrastructure were considered to be A$82 million/km (for a 4-lane freeway) based on CityLink construction costs of A$1.8 billion for a 22km length of road infrastructure. The period of operation was considered to be 25 years, where investors need to transfer the facility (road) back to the government after this period. In other words, the road investors have 25 years to recover their investment plus generating a profit.

$$\text{NPTR} = \sum_{y \in Y} \langle \frac{\left\{\sum_{a \in \overline{A}} \sum_{m \in M} [T_a^m - IC_a^m] * x_a^m * d_a . d_t\right\} - FM_a(C_a)}{(1+r)^y} \rangle - \langle ICC_a(C_a) \rangle \qquad (2)$$

where

$NPTR$: Net Present Toll Revenue (A$)
C_a : The capacity of road link a, $\forall\, a \in A \cup \overline{A}$ (veh/hour)
$FM_a(C_a)$: Fixed maintenance cost per year as a function of link capacity
$ICC_a(C_a)$: Infrastructure capital cost as a function of link capacity
Y : Number of years given (in PPP) for toll operation, $y \in Y \; and \; integer$
r : Discount rate (a non-negative real number)
d_t : Time in hours per year (an integer) (equals to 365*24)

2.2. Lower-level model

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

$$\min z(x) = \sum_a \int_0^{x_a} t_a(x)\, dx \; + \sum_a \sum_m x_a^m b_a^m \qquad (3)$$

where,
b_a^m: Bias value given in minutes w.r.t. vehicle type and respective toll charge, $a \in \overline{A}, m \in M$
q_{rs}: Trip rate between origin r and destination s
f_k^{rs}: Traffic flow on path k from origin r to destination s, $k \in K_{rs}$
$\delta_{a,k}^{rs}$= 1 if link a is part of path k connecting O-D pair r-s, and $\delta_{a,k}^{rs}$= 0 otherwise

The lower level model is multi-class user equilibrium and which corresponds to a variational inequality problem. An extension of the Frank Wolfe algorithm was used here, which is used in EMME (INRO Consultants Inc., 2017). The response to various toll charges by different vehicle types is incorporated into the equation via the bias value. The bias values used in this study was developed from a discrete choice experiment carried out in the Melbourne.

2.3. Multi-objective optimisation

The multi-objective optimization approach 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 not better than each other considering all of the objectives. These solutions are known as Pareto-optimal solutions or non-dominated solutions. Many algorithms have been developed to solve multi-objective optimization problems, including the Non-dominated Sorting Genetic Algorithm II (NSGA II) developed by Deb (Deb, 2002). The NSGAII has been used successfully in solving many multi-objective engineering problems (Bai, Labi and Sinha, 2012; Cao et al., 2011; Perera, Thompson and Wu, 2020; Kuriakose and Shunmugam, 2005; Milosevic and Begovic, 2003; Sarkar and Modak, 2005), and therefore is used for this study.

3. Case study

3.1. Network C

A hypothetical network from the literature - Network C (Figure 2) has been selected for this study to demonstrate the methodology.

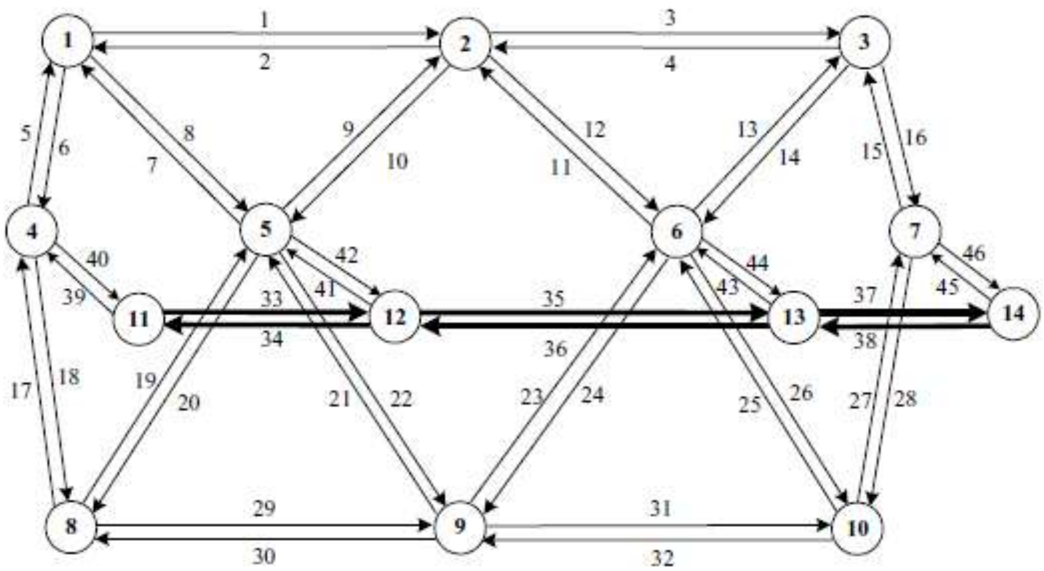


Figure 2: Structure of network C

There are 46 links and 14 nodes in this network. The capacities and link distances are similar to the one used by (Yang et al., 2004) and are summarized in Table 1. Links are divided into freeways, highways and local roads based on the capacities and free flow speeds of 100 kmph, 80 kmph and 60 kmph were assigned to three road types, respectively. A is the set of links without toll charges (highways and local roads/ road types 2 & 3) and $\overline{A}$ are the links with toll charges. $\overline{A} = \{33, 34, 35, 36, 37, 38\}$. The traffic flow on link $a \in A \cup \overline{A}$ is denoted by x_a and the link travel time is calculated based on the Bureau of Public Roads (BPR) travel time function. Original demand conditions stipulated by (Yang et al., 2004) were applied and no dynamic changes in demand or other variations are considered for simplicity.

Table 1: Network details

Link no.	Distance (m)	Capacity (veh/hr)	Road Type	Free Flow Speed (km/hr)	Link no.	Distance (m)	Capacity (veh/hr)	Road Type	Free Flow Speed (km/hr)
1	25000	4000	3	60	24	9000	4000	3	60
2	25000	4000	3	60	25	10000	4000	3	60
3	25000	4000	3	60	26	10000	4000	3	60
4	25000	4000	3	60	27	2670	6000	2	80
5	2670	6000	2	80	28	2670	6000	2	80
6	2670	6000	2	80	29	24000	3800	3	60
7	9000	4000	3	60	30	24000	3800	3	60
8	9000	4000	3	60	31	26000	4200	3	60
9	11000	4000	3	60	32	26000	4200	3	60
10	11000	4000	3	60	33	11670	10,000	1	100
11	9000	4000	3	60	34	11670	10,000	1	100
12	9000	4000	3	60	35	20000	16,000	1	100
13	9000	4000	3	60	36	20000	16,000	1	100
14	9000	4000	3	60	37	11670	10,000	1	100
15	2670	6000	2	80	38	11670	10,000	1	100
16	2670	6000	2	80	39	340	6000	1	100
17	2670	6000	2	80	40	340	6000	1	100
18	2670	6000	2	80	41	340	6000	1	100
19	9000	4000	3	60	42	340	6000	1	100
20	9000	4000	3	60	43	340	6000	1	100
21	10000	4000	3	60	44	340	6000	1	100
22	10000	4000	3	60	45	340	6000	1	100
23	9000	4000	3	60	46	340	6000	1	100

Note: Road type 1, 2 and 3 denote freeways, highways and local roads, respectively

3.2. CityLink toll scheme

Melbourne is a city with heavy internal freight movement compared to other Australian cities (Perera, Thompson and Chen, 2018) and CityLink is a major freeway going through the city. CityLink was constructed as with PPP and has been in operation since 1999. Since this 22km long toll road section goes right through the city, the toll charges for freight vehicles is of greater concern for freight operators and planners. Toll charges for commercial vehicles on this major toll road have raised by more than 125% within the last four years (Carey, 2017). This toll increase has had a significant impact on freight movement in and around the Melbourne metropolitan region and there is significant pressure on authorities from residents because there are more trucks on local roads lately. Consequently, CityLink tolls are used in this study to show the impacts.

4. Results and discussion

4.1. General Results

As explained above in the bi-level formulation, the upper-level has two objectives, minimization of total cost and maximization of Internal Rate of Return (IRR). These are two conflicting objectives where one single perfect solution cannot be achieved. As a result, Pareto-optimal solutions were found using the elitist non-dominated sorting genetic algorithm and the results are presented in Figure 3.

Figure 3 shows that the total cost can be minimized at the expense of IRR or IRR can be maximized at the expense of total cost. The minimum total cost that can be obtained based on this case study is A$ 18.52 million with an IRR rate of 4.27%. According to Truong, Partington and Peat, (2008) the cost of capital in Australia is between 5-6% and therefore any toll scheme producing an IRR above this limit can be considered as profitable. Having said that, from certain projects investors may expect a higher rate of return considering the associated risks. Thus, an IRR of 4.27% is unlikely to be accepted by the investors where less risk investments in the open market may receive about minimum 5-6% return.

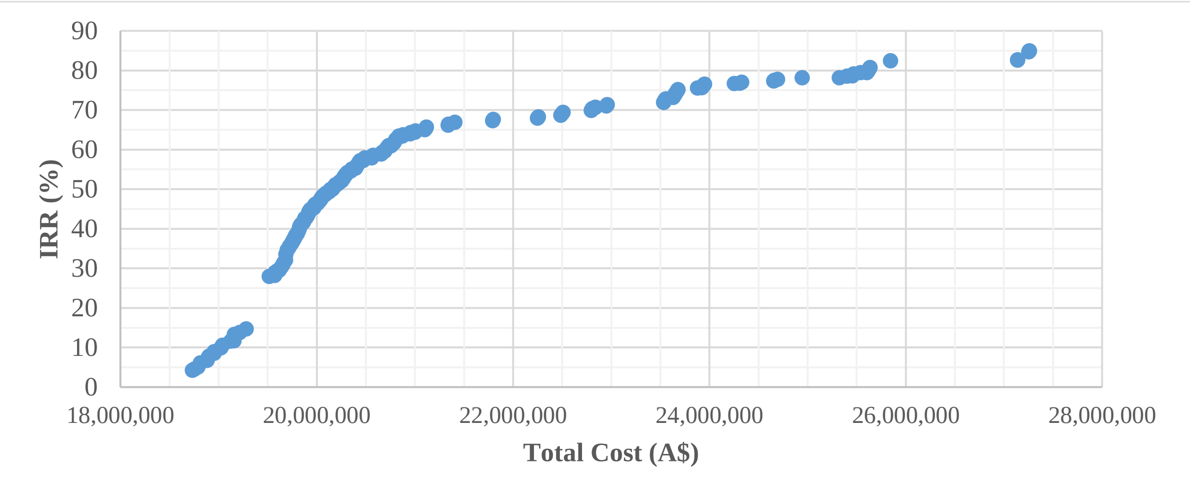


Figure 3: Total costs vs Internal Rate of Return (IRR)

As IRR increases, the total cost also increases at a lower rate at the beginning and at a higher rate after reaching A$ 21 million of the total cost. The maximum possible IRR (theoretically) that can be achieved from this project is 85%, which will be received at the expense of total user cost of A$ 27.26 million. Which is A$ 8.74 million higher than the minimum total cost amount. Since it is the government's responsibility to look after both users and the road investors the decision on what toll prices are appropriate is challenging to determine. At a glance it can be noticed that up until 65% of IRR the trade-offs (total cost increment rate) are less compared to IRRs above the 65% condition. In other words, a clear turning point in the total cost vs IRR curve can be seen around 65% of IRR with a respective total cost of A$ 21 million. This indicates that, under the given length of operational period and expected vehicle demand conditions, the best practical IRR would be 65% or less. Beyond this level total costs increase rapidly, at a higher rate than IRR increases, which is not a favorable condition from the policy makers view point.

However, the results from this study provide only the best alternatives (only optimal solutions are presented) available for the decision maker where they can make the best decision under prevailing conditions. The Pareto-optimal solution range covers the most optimal toll solutions from the user point of view to the most acceptable IRR percentage by the road investor. In other words, below the Pareto-front presented in Figure 3, there are large number of sub-optimal solutions (not shown in Figure 3) with various IRR values for any given total cost value and vice versa. Since our objective is to find the optimum IRR for given total cost, the Pareto-front shown in Figure 3 represents such solutions. Therefore, given the requirements (total cost or IRR) selecting an optimal solution is important rather than choosing a non-optimal solution wasting resources of multiple stakeholders unnecessarily.

One may argue that since total costs, more importantly the externalities are measured in dollar terms, why these costs and benefits (IRR) cannot be compared to arrive at one single solution. Environmental/social costs and user costs are not perfectly interchangeable costs even though they are measured in monetary terms (Neumayer, 1999; Wu et al., 2009). Thus, the multi-objective approach with Pareto-optimal solutions enables decision makers to evaluate trade-offs between manmade capital (user costs and toll revenue) and natural/social capital costs.

Since toll charges for each vehicle type are the decision variables considered here, it is worthwhile to look at what pattern it maintains with respect to multi-class toll charges with respect to various IRR percentages. Figure 4 depicts the multi-class toll charges with respective IRR for the above given Pareto-optimal solutions. This Figure presents a radar plot where x-axis shows (along the outer perimeter of the circle) the IRR as a percentage and corresponding toll charge per km is shown on the y-axis. Since this is a radar plot, lower toll charges per km are scattered around the centre of the plot whereas high charges are positioned towards the outer perimeter.

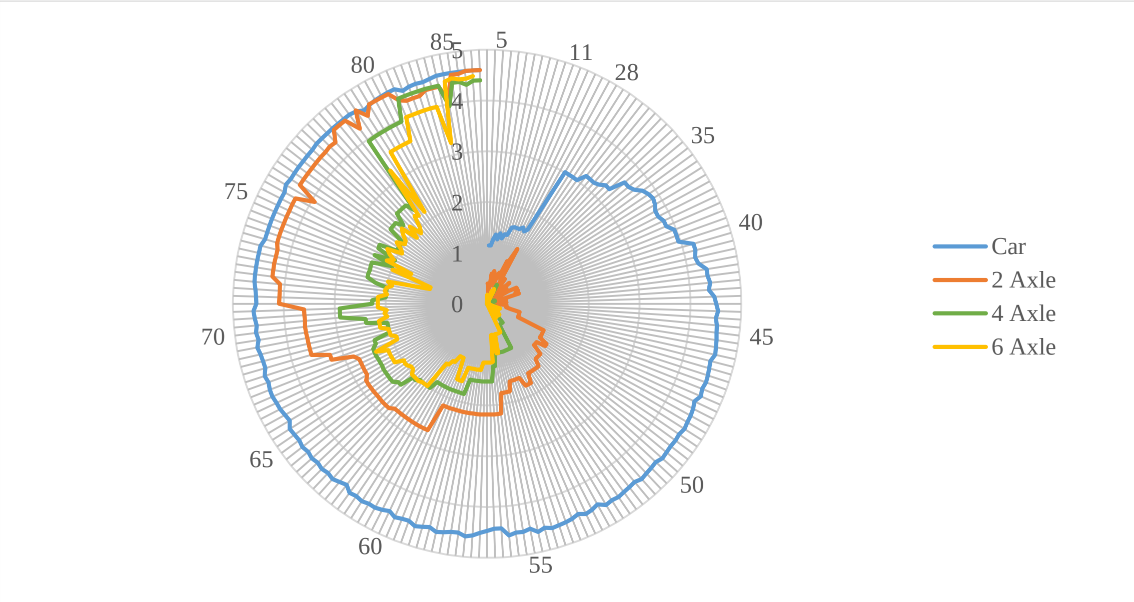


Figure 4: Optimal toll charges for each vehicle type under various IRR

From the Pareto-optimal solutions it can be seen that less charges are imposed on heavy vehicles (6 axles) compared to 4 axle types whereas cars are charged high at lower IRR values. This indirectly confirms the past finding that heavy vehicles produce more externalities on sub-standard roads and therefore with low toll charges heavy vehicles are less likely to avoid quality roads. Since the capacity on freeways is limited, light vehicles are compelled to shift to sub-standard roads. In other words, this model’s results can be used to encourage trucks to stay on freeways as much as they can in order to reduce total costs.

Even though governments are concerned about total costs, user costs are directly borne by the users themselves, not the government. Thus, an optimization was conducted excluding externalities from the total costs and respective IRR values were found. For completeness and to understand the relationship, an externalities and IRR curve was also developed. Both these Figures are given in 5(a) and 5(b).

It can be noted that the shape obtained in the Pareto-front in Figure 3 is similar to the curve presented in Figure 5(b), except the horizontal axis values are different. Figure 5(a) shows there is a direct relationship between user costs and IRR. Since IRR is calculated primarily based on toll revenue and toll revenue is a major component of user costs, it is apparent that user costs and IRR maintains a linear relationship. As a result, the externalities plus user costs curve (total cost) and the externalities only curve against IRR has to take similar shapes but with a different magnitude.

In the Pareto optimal solutions provided in the externalities vs IRR (Figure 5b), it's quite evident that IRR has a steeper increase compared to externalities at the beginning and it turns around beyond approximately 65% of IRR. Therefore, the investors have a high chance of earning 65% of IRR from their investment on this road project without disturbing externalities a lot. In other words, based on the case study traffic volumes and other conditions, road investors can earn up to IRR of 65% without diverting much heavy vehicle traffic to arterial roads, which makes less increase in externalities. However, this decision needs to be taken by the government authority considering the prevailing circumstances such as the current government policy (e.g. to reduce emissions, which is reflected in minimizing externalities), the market rate of return for similar projects with similar risks and the risk-free rate of return in the market, and other non-financial factors.

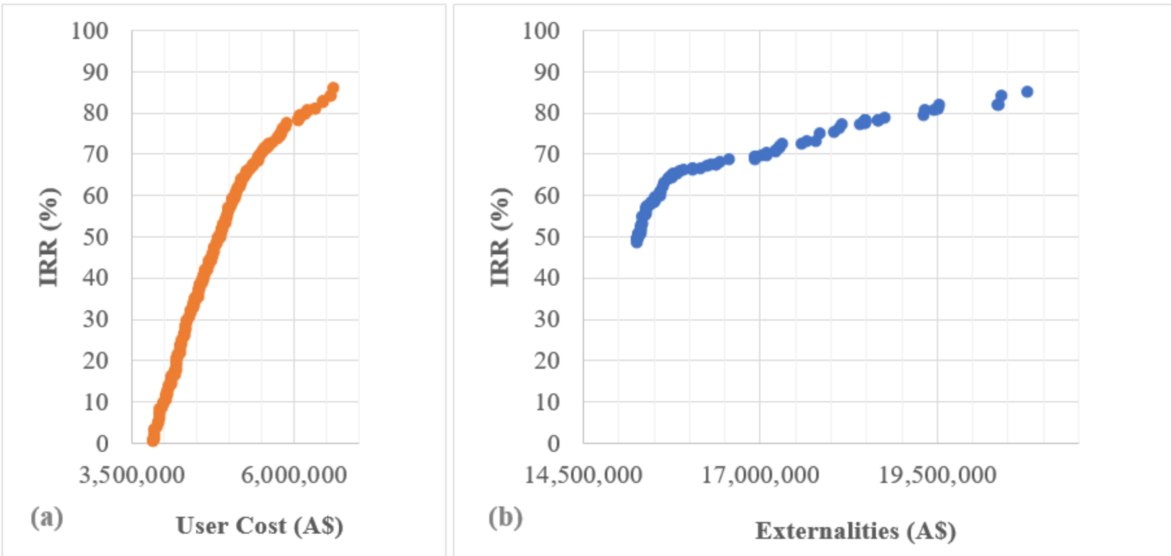


Figure 5: User costs and externalities vs IRR

As discussed above, since certain cost elements are either not perfectly interchangeable or borne by some stakeholder(s), the three main costs elements are analyzed separately below. Figure 6 depicts the multi-objective optimization output considering these three objectives. (since this is a 3-D figure shown in a 2-D platform some visualization is needed before reading it) It can be seen that when IRR increases both externalities and user costs increase and there is a clear turning point of the curve around 65% of the IRR. As explained above the rate at which costs are increasing as compared to IRR is high above the turning point.

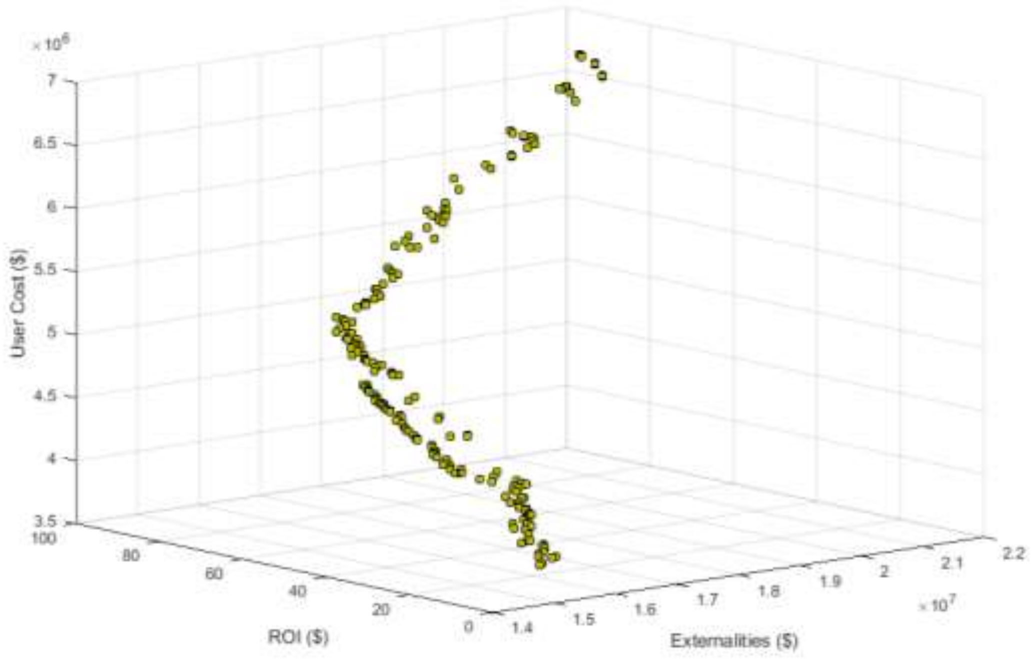


Figure 6: Trade-offs between user costs, externalities and IRR

Figure 7 depicts the toll ratio of multi-class vehicles for the Pareto-optimal solutions obtained. For the majority of these solutions, cars are generally charged more, whereas 6 axle vehicles are charged less. Among these optimal solutions, toll charges for freight vehicle (2 axles, 4 axles and 6 axles) would increase only for very high IRR values which are beyond supernormal returns (IRR above 50%). The acceptability of these toll schemes by various stakeholders is another prevailing problem but not within the scope if this study. Thus, it is not discussed in this paper but published in Perera and Thompson, (2021a and 2021b).

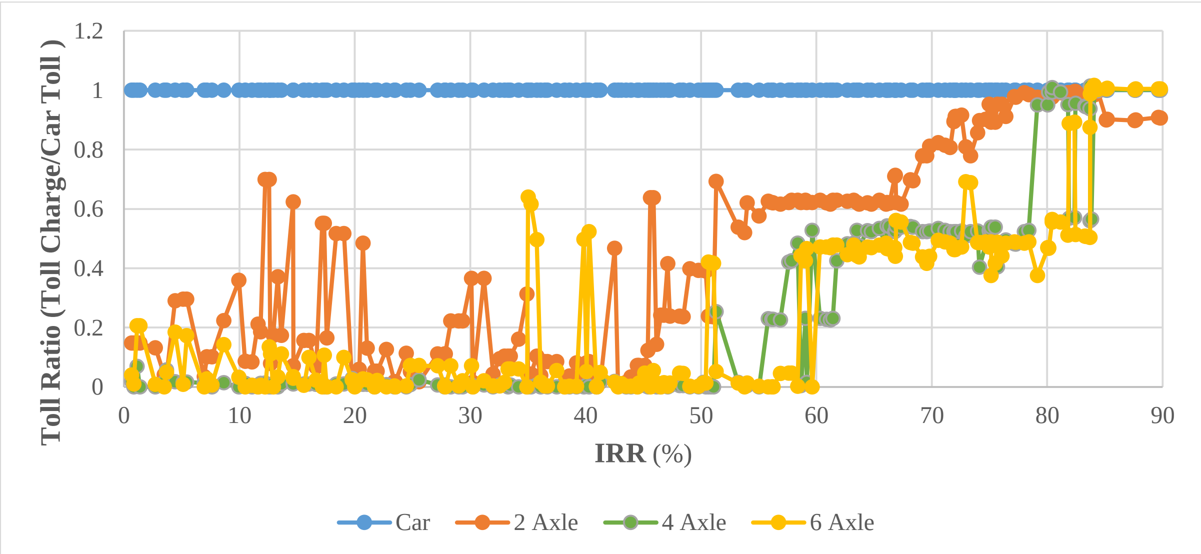
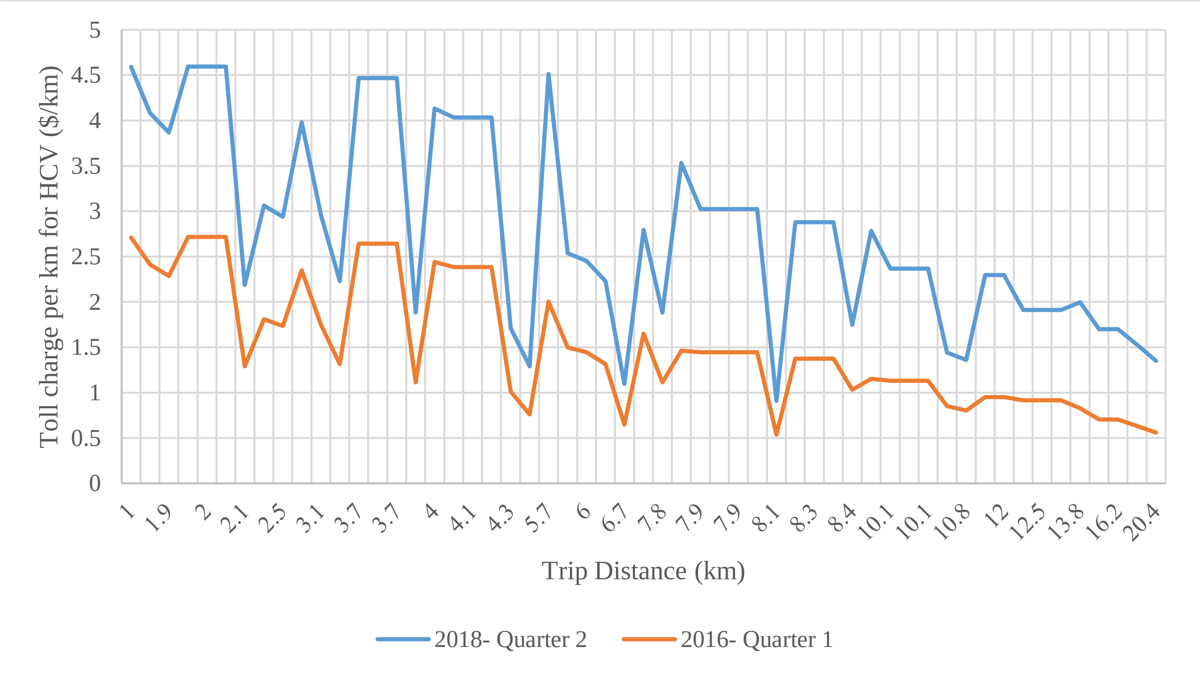


Figure 7: Toll ratio (Toll charge/car toll) for solutions obtained in the Pareto front

4.2. Results using CityLink toll scheme

As mentioned above since there was a significant toll increase in the CityLink in the recent past and considering the variation in charges on various road sections an analysis was done to evaluate the CityLink toll charges. Figure 8 below depicts the comparison of CityLink toll charges for heavy vehicles per km based on different trip OD pairs and associated trip distances. The analysis is only done for heavy vehicles since it can be observed that on CityLink a fixed toll ratio is maintained between heavy vehicles and other vehicles. When comparing 2016 and 2018 toll charges for various trip lengths as shown in Figure 8 it can be noted that toll charges for heavy vehicles have risen rapidly over the last two years (this study was done in 2019). A minimum of 70% increase was recorded per km basis and an increase in toll charges for heavy vehicles in this magnitude has a significant impact on the City Logistics operations. Therefore, the present toll charges on CityLink road was used for illustration purpose in this study.



Note: Toll charges are calculated based on the published information from April-June 2018 and Jan-March 2016 (www.citylink.com.au)

Figure 8: Toll charges comparison for CityLink based on the trip distance for heavy vehicles

If the current toll charge rates in Melbourne's CityLink are applied to the test network for illustration purposes, i.e. the cars: light commercial vehicles (LCV): heavy commercial vehicles (HCV) toll ratio of 1: 1.6: 3, then the respective externalities and user costs are A$ 18.5 million and A$ 4.02 million, with no positive IRR. This was assuming the lowest toll charge for HCV on CityLink, which is A$ 0.90/km. However, the present toll charges for HCV on CityLink varies from A$ 0.90/km to A$ 4.59/km (See Figure 8) and it is clear from this study that CityLink investors cannot survive by charging the lowest amount for HCV (because IRR calculated above is not positive). Therefore, CityLink investors approach is obvious where they have to charge a high toll for HCV when maintaining the toll ratio for survival.

From the set of optimal solutions obtained (Figure 6) trade-offs for the above scenario can be calculated as follows. For an externality cost of A$ 18.5 million, an IRR of 75% can be possibly generated by changing the toll charges for multi class vehicles deviating from the present ratio of 1:1.6:3. Or else given the user cost as A$ 4.02 million, by using the respective optimal solution the investors should able to generate an IRR of 10%. Even if the maximum charge is imposed on HCV (A$ 4.59/km), under the prevailing ratio, they would only earn an IRR of

44.5%. Therefore, CityLink tolls are set in such a way that they can earn some revenue (positive IRR) by varying the per km charge for HCV but keeping the ratio fixed for other vehicle types.

The trade-offs calculation clearly shows how inefficient the current toll price settings are favoring neither the road investor nor users/public. And having a fixed ratio for multi-class vehicles worsens the situation. It is shown from the case study that optimal solutions provided by the model in this study can generate efficient and acceptable outcomes for all key stakeholders, which are road investors, users and the general public.

This methodology has been applied to a real world network in Melbourne and the results have been verified Perera, Thompson, and Wu, (2021). Therefore, this method can be applied to other networks with toll roads and optimum toll charges for multi-class vehicles can be found favoring all stakeholders.

5. Conclusions

Road investors are trying to make more revenue by charging higher tolls for heavy vehicles and they do not consider the externalities generated by heavy vehicles in urban transportation systems. This has led to various problems in City Logistics and stakeholders are looking for sustainable solutions. This study presents an innovative way of reducing total costs for freight transportation in an urban condition by optimizing toll charges for multi-class vehicles on freeways. Externalities are considered as part of the cost for freight transportation to eliminate cross-subsidization of freight transportation cost and to further reveal the real transportation cost for freight with no concessions.

Using multi-objective optimization analysis, the trade-offs between different cost elements and IRR were investigated under various toll schemes. Since these cost elements are not interchangeable, the relationships between different cost elements and IRR have been illustrated. This will enhance the decision makers' knowledge of the impacts from different toll schemes. When the optimal solutions are compared with an existing tollway scheme, it was revealed that the present system is inefficient in terms of toll revenue generation, minimizing user costs as well as minimizing externalities. Therefore, the method proposed in this study is able to minimize total users' costs by virtue of setting tolls for multi-class vehicles.

In the future, this method can be used to identify optimal toll charges for each vehicle type on a freeway satisfying all stakeholders and to reduce the un-necessary burden on users, residents and the general public.

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