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ASSESSING THE SOCIAL COSTS OF MIXED TRANSPORT SYSTEMS WITH A DOMINANCE OF MOTORCYCLES

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Abstract

When undertaking strategic planning to identify potential options for a detailed assessment, it is important to compare the total costs of existing mixed transport systems with the introduction of different new public transport (PT) modes. Hence, this study develops a social cost model for situation of mixed transport system which has a dominance of motorcycles where a new PT technology (e.g. Bus Rapid Transit - BRT, Monorail or elevated Metro) or an exclusive bus lane is being considered. The innovative aspects of this research are to develop equations to estimate the average operating speed of each mode and to the allocation of infrastructure costs to several transport modes sharing the facilities in motorcycle dominated mixed traffic environments. Based on a four-lane per direction mixed traffic corridor in Hanoi, Vietnam, the results show the lowest average social cost (ASC) mixed transport systems for different ranges of demand. Moreover, all mixed traffic options with BRT, Monorail, elevated Metro or exclusive bus lanes are better than the existing situation in terms of ASC and it is suggested that their feasibility is examined in a detailed assessment. The mixed transport social cost model can be modified to suit other local conditions where conventional bus, car and motorcycle share facilities and a new PT mode is operated. Additionally, transport planners and decision makers in such local situations, which are particularly common in South East Asia, can draw on the findings of this study.

Keywords: social cost model; private transport; public transport; mixed transport; motorcycle; Vietnam.

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1. Introduction

Private transport including car and motorcycle has increased rapidly in mixed traffic environments, especially in Asian countries (e.g. Indonesia, Malaysia, Thailand and Vietnam). The dominance of motorcycles in mixed transport can lead to transport problems such as traffic congestion, air pollution, noise pollution and traffic accident [1, 2]. One solution to these challenges is investment in new innovative PT projects such as BRT, Metro and Monorail, rather than the investments in conventional bus that has been common in several countries such as Malaysia and Vietnam [3, 4]. However, there seems to be very little evidence on the comparative costs for each mode in a mixed transport system with an abundance of motorcycles, as well as comparisons between mixed traffic systems with the introduction of different PT modes. These comparisons at a strategic planning level can be essential for a feasibility analysis of potential infrastructure options in a more detailed assessment. Hence, this study assesses several mixed transport infrastructure options with new different PT technologies by comparing their total social costs on an urban corridor where motorcycles are dominant. The structure of this paper is as follows. Section 2 reviews literature on comparative cost models of

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individual transport mode and mixed transport systems. A mixed transport social cost model is developed in Section 3. Section 4 introduces a case study in Hanoi, the capital of Vietnam. The key results of the model are illustrated in Section 5. Some conclusions and potential future work are discussed in Section 6.

2. A review of comparative cost models

As detailed in [5], several studies on comparative costs of transport modes have been conducted following the pioneering study of [6]. This original study compared different modes including rail, express bus, flier bus and automobile for 6-mile, 10-mile and 15-mile corridors in medium and high population densities, in terms of average passenger trip cost. The social costs included operator cost and user cost. The results showed that costs for all PT services decrease when hourly passenger volume along the corridor increases. For comparisons between transport modes, the average cost of passenger car was the smallest at the demand of about 5,000 passengers per direction per hour. In addition, the rail systems were the cheapest in the high population density areas, whilst bus systems were the cost effective mode in medium population densities [6].

The authors in [7] compared bus rapid transit, light rail and heavy rail transit over a radial trunk network with the objective of minimising the total costs (operator and user costs). The route length and the average trip distance were 30 km and 10 km correspondingly. The optimisation of the total costs was based on the frequency and number of PT lines that impact on walking, waiting and in-vehicle time for PT users as well as on the total operator costs (a combination of land, infrastructure and operating costs). Based on data from Australian cities, the results suggested that BRT is the most cost-effective mode in most of the scenarios analysed due to lower operator costs, access time cost and waiting time cost. Light rail (heavy rail) transit is more cost effective than BRT only if the speed of these technologies is at least five (nine) km/h higher than the BRT speed of 31 km/h.

Then, the external cost was added to the social cost model in [8]. The total social costs of 15 different PT modes including conventional bus, light rail and heavy rail system, and personal rapid transit, were compared on a 12 km route corridor at a strategic planning level. Average social cost in pence per passenger-km is one of the final outputs of the comparisons. The results showed that the conventional bus is cheapest when daily demand is lower than 40,000 passengers per day. Suburban heavy rail has advantages for demand levels ranging from 40,000 to 88,000 passengers per day, whilst Underground is the best mode at demand levels of higher than approximately 100,000 passengers per day.

In addition, the authors in [9] assessed the total costs of private transport (passenger car) versus public transport (bus) in the Auckland region of New Zealand. The total costs included the external and internal costs. The former consists of accident costs, air pollution cost and climate change cost while the latter is direct spending by the government to run the transport system. That study did not consider vehicle capital cost and other costs such as congestion-related delay costs. The results showed that the external costs of cars and buses account for around 53% of the total costs. In addition, the total costs of cars per passenger-kilometre are twice those of buses in Auckland.

In a different study, the authors in [10] compares the full costs of seven passenger modes including heavy rail transit, light rail transit, arterial bus, bus rapid transit, expressway bus flier, automobiles and bicycles in hypothetical radial and circumferential commuting corridors in large Chinese cities. The full costs of each transport mode consisting of capital, operation, user time, safety and environmental costs are estimated. The average cost per passenger-km for each mode is calculated by dividing the full costs by traffic volumes. In general, the average cost of commuting by one or more forms of bus transit or bicycle is smaller than that cost of automobile or rail. Moreover, the average cost of passenger car travel is higher than that of bus even at low traffic volumes. However, in ring corridors, rail and bus have the smallest average costs under certain conditions while bus is better than bicycle in some cases.

Furthermore, the authors in [11] developed a social cost model for eight transport modes on a 7 km route corridor in Hanoi, Vietnam. The eight modes, which include passenger car, motorcycle, Taxi, Uber, conventional bus, BRT, elevated Metro and Monorail, are compared for fixed demand levels ranging from 1,000 to 700,000 passengers per direction per day, in terms of average social cost. The results showed that car, Taxi and Uber are the most expensive modes at any demand levels whilst motorcycle has the smallest average social cost at low demand levels. Moreover, conventional bus or BRT have advantages for medium demand levels between 35,000 and 220,000 passengers per direction per day. Additionally, Monorail and two exclusive bus lanes per direction options have the lowest average social cost when demand levels range from 220,000 to 315,000 passengers per direction per day. At the highest demand levels, elevated Metro is the best mode [11].

In general, these previous studies focused on comparative costs of an individual transport mode. However, there seems to be very little evidence on cost models of mixed transport systems where several existing modes (e.g. car, motorcycle and bus) share infrastructure facilities, as well as a lack of comparative costs of different mixed traffic options where new PT technologies (e.g. BRT, Metro, Monorail) are introduced. Two main issues are addressed as follows. For different demand levels of a mixed traffic corridor, it seems to be difficult to estimate the average operating speed of each mode, in particular in a situation where motorcycles are dominant. Another issue relates to the allocation of infrastructure costs to several transport modes sharing the facilities. As a result, this study extends the existing literature in two respects. Firstly, a social cost model for mixed transport including bus, car and motorcycle, which has not previously been considered in the literature, is developed by overcoming the two issues above. Secondly, the average social costs of four mixed transport systems and the introduction of a new PT mode (BRT, Monorail or elevated Metro) or exclusive bus lanes are calculated for an urban corridor. Potential PT modes can be then suggested for a more detailed assessment by comparisons with the existing situation in terms of ASC.

3. Mixed transport social cost model

This study develops a social cost model for mixed transport based on the social cost model of single mode for one urban corridor in [11]. In the social cost models of individual private transport or public transport modes, only one mode was assumed to use the facility for fixed daily demand ranging from 1,000 to 700,000 passengers per direction per day (pdd). The daily passenger demand is the sum of the demand for peak and off-peak periods. The innovative aspects of this research are to develop equations to estimate the average operating speed of each mode and to the allocation of infrastructure costs to several transport modes sharing the facilities in motorcycle dominated mixed traffic environments.

In the study of [11], the total social costs of each transport mode consist of total operator costs (or infrastructure operator costs for private transport), total user costs (or vehicle user cost for private transport) and total external costs. For all modes, the total external costs cover accident costs, noise pollution costs, air pollution costs and climate change costs. Elements of total operator costs and total user costs and their calculations are different for dissimilar modes. Firstly, the operator costs of PT modes include both operating costs and capital investment costs, which are estimated by using the Fully Allocated Costs model [12, 13]. Walking time, waiting time and in-vehicle time were included in the PT user costs. Secondly, the infrastructure operator costs for private transport (PRV) include infrastructure costs, maintenance costs and parking costs. Operating costs for users, private vehicle capital costs, travel time and congested-related delay costs are included in the vehicle user costs for PRV. The average social cost (ASC) of each transport mode is calculated as:

$$ASC = TSC/PKM \tag{1}$$

where PKM is total passenger-kilometres, calculated by the product of total passenger demand for each transport mode and average passenger journey length.

Similarly, the average social cost of a mixed transport option including several modes is estimated as:

$$ASC_{all} = \frac{TSC_{all}}{PKM_{all}} \tag{2}$$

where PKM_{all} is the annual passenger kilometres travelled by all transport modes, TSC_{all} is the annual total social costs of all transport modes on a mixed transport corridor.

The total social costs of a mixed transport system are the sum of the total social costs of public transport and private transport, except infrastructure costs. The infrastructure costs of a mixed transport system include the infrastructure costs of the segregated public transport mode (e.g. Metro and Monorail) and the infrastructure costs of mixed lane facilities. The infrastructure costs of the mixed lane facilities are allocated to transport modes sharing facilities (e.g. car, motorcycle and conventional bus). Based on the study in [14], the percentage of the infrastructure costs of the mixed lane facilities allocated to each vehicle type is estimated in Eq. (3). It is assumed that eighty-five per cent of the infrastructure costs reflect the capacity needs in terms of different types of vehicles. These costs are allocated in terms of passenger car units (PCU). Fifteen per cent of the infrastructure costs are related to heavy duty vehicles in particular (to reflect increased road damage) and are allocated in terms of gross weight vehicle-km [15].

$$\sigma_i = 0.85*\frac{\delta_i*APVKT_i}{\sum \delta_i*APVKT_i} + 0.15*\frac{GMWPV_i*APVKT_i}{\sum GMWPV_i*APVKT_i} \tag{3}$$

where, $GMWPV_i$ is the gross maximum weight of vehicle type i (tonnes), $APVKT_i$ is the annual kilometres travelled by vehicle type i (km/year), σ_i is the percentage of the total infrastructure cost allocated to each vehicle type i, δ_i is the PCU value for vehicle type i. These values for motorcycle and bus are equal to 0.4 and 2.0 respectively [16]. In a motorcycle dominated transport network, a bus and a car are equivalent to 10.5 and 3.4 motorcycle equivalent units (MCU) correspondingly [17]. These MCU values are used in this study rather than the PCU values in a car dominated transport network.

For mixed traffic where motorcycle and other modes share facilities, the speed-flow-density relationships were investigated by using a motorcycle equivalent unit model [17–19]. To convert other transport modes into Dynamic Motorcycle Unit (MCU) by using a formula as follows:

$$MCU_i = \frac{V_{mc}/V_i}{S_{mc}/S_i} \tag{4}$$

where MCU_i is the Motorcycle Equivalent Unit of vehicle type i, V_{mc}, V_i are the mean speed of motorcycles and vehicle type i, respectively (km/h), S_{mc}, S_i are effective space for one motorcycle and one vehicle type i respectively (m^2). The effective space for one vehicle is defined as the necessary space of a rectangle for this vehicle to maintain its desired speed.

In addition, the key intermediate output in the mixed transport social cost model is operating speed, which is used to calculate most of cost elements such as travel time costs and delay costs in the private transport social cost model, and user costs in the public transport social cost model. Based on the speed equations in [8, 20, 21], and [11], the average speed of a new exclusive public transport technology (VPT) is calculated as follows:

$$\begin{cases} V_{PT} = V_{NoCap} & \text{if } Q < C \\ V_{PT} = \dfrac{L}{\dfrac{L}{V_{NoCap}} + 0.5\,W\left(\dfrac{Q}{C} - 1\right)} & \text{if } Q \geq C \end{cases} \tag{5}$$

where W is the peak period duration in hours. The default value can be 1 hour [20]; L is the length of the study corridor in km; C is the infrastructure capacity, which is the maximum possible number of vehicles per lane (for road-based systems) or per track (for rail-based systems), and is calculated from the safety headway; Q is the PT demand, which is estimated by dividing the passenger demand by occupancy of PT modes; V_{NoCap} is the PT operating speed in m/s, which accounts for the stop density constraint without the capacity constraint [8], which is shown as:

$$V_{NoCap} = \frac{V_{\max} * A * D_{stop} * 1000}{\left(\dfrac{V_{\max}}{3.6}\right)^2 + A * \left(D_{stop} * 1000 + T_{dwell} * \dfrac{V_{\max}}{3.6}\right)} \tag{6}$$

where, V_{NoCap} is the transit operating speed (km/h); A is the acceleration and deceleration of the vehicle (m/s^2); D_{stop} is an average distance between stops/stations (km); T_{dwell} is an average vehicle dwell time per stop/station, including time required to open and close the doors; and passenger boarding/alighting time (seconds); V_{max} is the maximum possible running speed (km/h).

Table 1. Flow-speed relationship and capacity for three types of mixed traffic corridors [17]

	Four lanes per each traffic direction	Three lanes per each traffic direction	Two lanes per each traffic direction
Traffic flow (F) and mean stream speed (S) relationship	F = 5,852*S* exp(-S/11.3)	F = 5,271*S* exp(-S/11.2)	F = 2,951*S* exp(-S/12.3)
c parameter (shown in Eq. (9))	11.3	11.2	12.3
Capacity (MCU/direction/hour)	24,335	21,725	13,358

Because the social cost model for mixed transport is calculated for different demand levels, it is essential to determine the speed of mixed traffic with a dominance of motorcycles corresponding to a given traffic flow (or passenger demand). However, there are very little studies on this problem. As a result, this study improves the flow-speed relationships expressed as exponential function in [17] by using the Lambert W function to estimate the speed of mixed traffic corresponding to a given traffic flow. By using a MCU model, the authors in [17] produced the flow-speed relationships and capacity for three types of urban mixed traffic corridors, which are shown in Table 1.

Suppose that two variables x and z are related as:

$$xe^x = z \tag{7}$$

[22] cited that [23] suggested a function for solving Eq. (7) and rearranged it as:

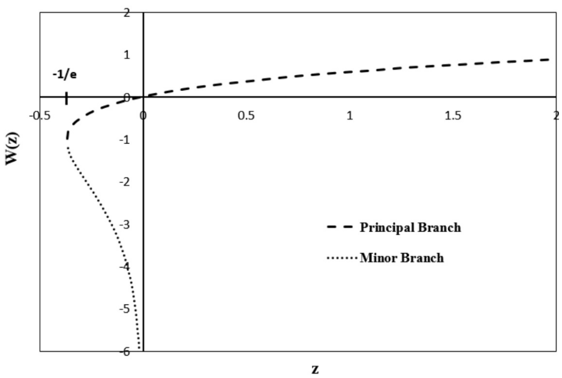
$$x = W(z) = \sum_{n=1}^{\infty} \frac{(-n)^{n-1}}{n!} z^n \tag{8}$$

[22] cited that [24] obtained a solution of the trinomial equation $x = q + xm$. And then the Euler's work was an extension of the research of Lambert. Therefore, the function W was named Lambert W in his honour. Speed can then be expressed as [22]:

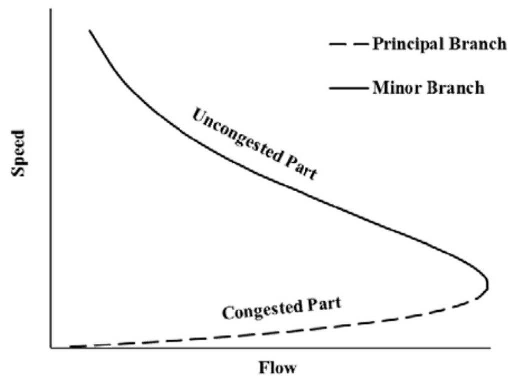
$$v = -c\, LambertW\left(-\frac{q}{k_j c}\right) \tag{9}$$

where v is the speed (km/h), q is the flow (vehicle/h), k_j is the density for a traffic jam (or jam density) (vehicle/km), c is a constant, which is obtained for a particular roadway.

The minor branch of the Lambert W function shows the speed corresponding to the uncongested part of the speed-flow curve whereas the principal branch expresses the speed in the congested part (see Fig. 1). This means that the uncongested part shows the smaller solution of the Lambert W function [22].



(a)



(b)

Figure 1. (a) Two branches of Lambert W function and (b) Flow-speed relationship in the Greenberg model by using the Lambert W function

Source: [22]

The MATLAB program can solve the Lambert W function. Indeed, for real x where $-1/e < x < 0$, the equation has exactly two real solutions. The larger solution for congested condition is represented by $y = lambertW(x)$ and the smaller solution for uncongested condition is shown by $y = lambertW(-1, x)$ [25].

As a result, an application for estimating speed corresponding to a given uncongested traffic flow in Eq. (9) is suggested by using the Lambert W function in MATLAB. To validate the application of the suggested speed equation above, the following equation for a four-lane per direction corridor in Table 1 is chosen to test the accuracy of this application.

$$q = 5{,}852 * v * \exp\left(\frac{-v}{11.3}\right) \tag{10}$$

where, v is the speed (km/h), q is the flow (MCU/h), the c constant is 11.3 while the jam density is 5,852 motorcycle/km [17].

Based on Eq. (9), the speed is therefore expressed as a function of the flow:

$$v = -11.3\, LambertW\left(-\frac{q}{66{,}127.6}\right) \tag{11}$$

The test includes the following three steps. The first step is to substitute all integer numbers from one to the maximum flow of 24,335 in Eq. (11) to obtain the values of speed v. Then, all these values of speed v are substituted in Eq. (10) to get the values of flow q. The next step is that 24,335 new values of flow q are compared with a range of integer numbers from one to 24,335. The results show that all differences are less than 0.033%. This proves that the Lambert W function can be acceptable to estimate the speed of mixed traffic corresponding to a given traffic flow.

To conclude, the mean stream speed of all modes on a mixed traffic corridor is estimated as:

$$V_{mean} = \begin{cases} min\left[-c*lambertW\left(-1, -\dfrac{q}{k_j c}\right), V_{max}\right] & \text{if } q \le C \\ \dfrac{L}{\dfrac{L}{v_0} + \dfrac{1}{2} * W * \left(\dfrac{q}{C} - 1\right)} & \text{if } q > C \end{cases} \tag{12}$$

where, V_{mean} is the mean stream speed on links (km/h); k_j is the density for a traffic jam (or jam density) (MCU/direction/km); c is a constant, which is shown in Table 1; q is the all mixed traffic flow (MCU/direction/h); V_{max} is the maximum operating speed on the corridor (km/h). This is the speed limit on the corridor; C is the highway capacity (MCU/direction/hour), which is shown for each type of corridor in Table 1; L is the length of the corridor (km); W is the peak period duration in hours. The default value is 1 hour.

The speeds of motorcycle and car in mixed traffic are estimated as V_{mean} in Eq. (12) while the speed of bus in mixed traffic is calculated as:

$$V_{bus} = \frac{V_{mean}*A*D_{stop}*1000}{\left(\dfrac{V_{mean}}{3.6}\right)^2 + A*\left(D_{stop}*1000 + T_{dwell}*\dfrac{V_{mean}}{3.6}\right)} \tag{13}$$

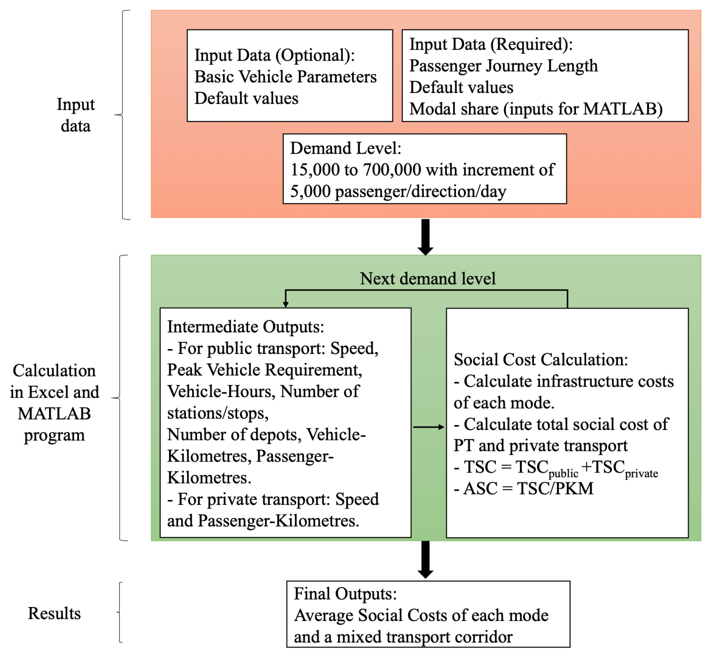


Figure 2. Operating procedure of the mixed transport social cost model

The social cost model for mixed transport estimates operator cost, user cost and external cost for each transport mode on a mixed transport corridor for different demand levels. The mixed transport corridor has two, three or four lanes per direction. The total social cost and average social cost of each mode and the mixed transport system are then calculated. The operating procedure of the mixed transport social cost models is shown in Fig. 2. An example calculation of estimating the total social cost and average social cost of an existing mixed transport system is illustrated in Table A.1 in the Appendix A.

4. Case study

The Nguyen Trai - Tran Phu - Quang Trung (NT-TP-QT) corridor (in Fig. 3) with a length of 7.0 km, which is a four-lane per direction major arterial in Hanoi, Vietnam, is selected as a case study for the following reasons. Firstly, motorcycles are dominant on this corridor, which can be found in many cities in other countries such as Taiwan [1], Malaysia [26], Indonesia [27] and Thailand [28]. Secondly, elevated Metro has been operated on this corridor since 2021 [4]. This will permit a retrospective strategic evaluation of this PT investment.

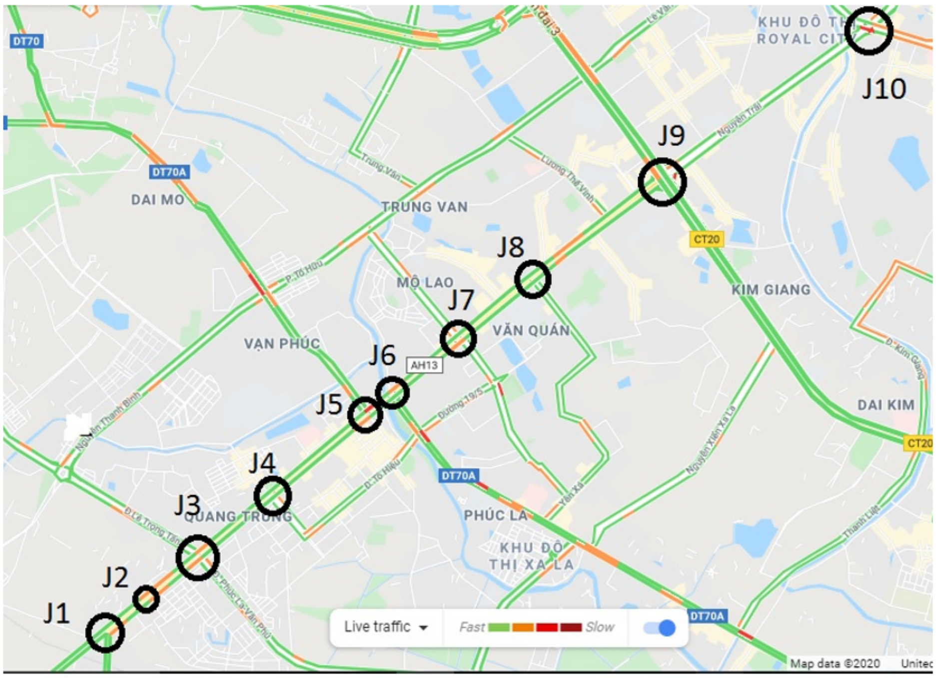


Figure 3. Location of Nguyen Trai - Tran Phu - Quang Trung corridor

The basic input parameters in the mixed transport social cost model for the Hanoi case study are based on the study in [11] that used the secondary data provided by companies and local governments. Six transport modes including conventional bus, BRT, elevated Metro, Monorail, passenger car and motorcycle, are considered in this study. Table 2 shows their characteristics, default unit capital costs and life expectancies of these modes. The unit PT operator costs are described in Table 3. Table 4 illustrates the default external unit costs by the six modes. The value of time for different modes is shown in Table 5. The daily demand, which is assumed to be from 06:00 to 21:00, is split into the four periods including the peak hours (2 hours), peak periods (3 hours), mid-day off-peak (7 hours) and early morning-late evening off-peak (3 hours), which are described in Table 6.

In order to identify potential new PT modes on the corridor at a strategic planning level, the existing situation is required to compare with new options. As a result, traffic demand was collected

Table 2. Vehicle characteristics, default unit capital costs and life expectancies [11]

Transport modes	Person capacity (pax)	Occupancy (pax)	Vehicle length (m)	Max. speed (km/h)	Infrastructure capacity (vehicles/h per lane/track)	Vehicle costs (£ thousand/ vehicle)	Life expectancies in years (Vehicle/ Infrastructure)
Exclusive conventional bus	80	33	12	55	225	182.1	20/20
BRT	90	41	12.3	60	240	455.4	20/20
Elevated Metro (4-car unit)	820	287	80	80	138	3,045.3	25/50
Monorail (4-car unit)	360	126	50	80	156	2,000	25/50
Passenger car	5	1.57	-	55	-	15.6	20/20
Motorcycle (125cc)	2	1.22	-	50	-	1.5	13/20

Notes: All costs are in 2015 prices. The discount rate (DR) for capital investment for the Hanoi case study is set at 12% [29].

Table 3. Default unit PT operator costs

Cost components	Vehicle Hours	Vehicle Distance	Peak Vehicle Requirement	Track/lane Distance	Station /Stop	Depot
Units	£2015 per VH	£2015 per VKM	£2015 per PVR pa	£2015 per track/lane distance pa	£2015 per Station/stop pa	£2015 per depot pa
Conventional bus	21.14	0.55	15,384.70	1,204,909.02	182.89	60,964.43
BRT	17.66	0.55	62,355.85	1,204,909.02	109,948.03	60,964.43
Elevated Metro	444.42	7.87	442,502.85	1,836,945.18	2,243,595.49	5,483,418.43
Monorail	331.09	5.51	178,499.96		1,806,249.95	

Table 4. Default external unit costs by modes in the Hanoi case study, 2015 prices [11]

Transport modes	Air pollution (pence/pax km)	Noise pollution (pence/pax km)	Climate change (pence/pax km)	Accidents cost (pence/pax km)
Bus	0.10	0.04	0.0089	0.01
BRT	0.10	0.04	0.0078	0.01
Monorail	0.0008	0.0014	0.0009	0.0001
Elevated Metro	0.0008	0.0017	0.0005	0.0001
Car	0.11	0.06	0.06	0.10
Motorcycle	0.12	0.15	0.03	1.92

Table 5. Value of time for different transport modes in Hanoi, 2015 prices [11]

Transport mode	Value of time (£)
Car	0.77
Motorcycle	1.54
Public transport	0.54

on the corridor from 16:30 to 18:30 on Monday 16 April 2018, which covers both the afternoon peak period and afternoon peak hour in Table 6. 100 surveyors including one author participated in the data collection process. Due to time and labour force limit, the primary data for the off-peak period could not be collected on-site. The surveys at all ten junctions on the corridor (shown in Fig. 3) were carried out to observe the movements of all types of vehicles. The method for collecting data is that one group of surveyors at each junction used cameras to record all movements of vehicles. Then, the traffic volume of each mode for each movement was counted in-house from the video recordings. The results show that a majority of vehicles on the corridor are conventional bus, car and motorcycle whilst other modes (e.g. bicycle, truck etc.) having very minor shares can be ignored in the social cost model. Hence, the modal shares of bus, car and motorcycle are estimated as 8.81%, 13.72% and 77.47% respectively. Moreover, according to the passenger demand split into different times shown in Table 6, the daily passenger demand for this corridor is calculated as 407,700 pdd.

Table 6. Passenger demand split into different times in the Hanoi case study [11]

Period	Time-time	Period duration (hours)	Split rate for one hour period	Daily split
Early morning off-peak	6:00-7:00	1	4.0%	4.0%
Morning peak hour	7:00-8:00	1	10.0%	10.0%
Morning peak period	8:00-9:00	1	7.5%	7.5%
Mid-day off-peak	9:00-16:00	7	6.5%	45.5%
Afternoon peak period	16:00-17:00	1	7.5%	7.5%
Afternoon peak hour	17:00-18:00	1	10.0%	10.0%
Evening peak period	18:00-19:00	1	7.5%	7.5%
Late evening off-peak	19:00-21:00	2	4.0%	8.0%

The following suggested options are compared in the mixed transport social cost model.

- *Base option*: This is the existing situation where conventional bus, car and motorcycle share a four-lane (per direction) corridor.

- *Option 1*: Combination of four-lane (per direction) corridor where a segregated elevated Metro service is introduced to replace the existing bus services and the four existing mixed lanes per direction are for car and motorcycle sharing.

- *Option 2*: Combination of four-lane (per direction) corridor where a segregated Monorail service is introduced to replace the existing bus services and the four existing mixed lanes per direction are for car and motorcycle sharing.

- *Option 3*: Combination of four-lane (per direction) corridor where there is an exclusive BRT lane with three mixed lanes for car and motorcycle per direction. One existing mixed lane is converted into an exclusive BRT lane per direction.

- *Option 4*: Combination of four-lane (per direction) divided corridor where there are an exclusive bus lane and three mixed lanes for car and motorcycle per direction. There are no new PT modes, however, one existing mixed lane is converted into an exclusive bus lane per direction.

Based on the existing chosen corridor with four lanes per direction, these suggested options might be potential when a new public transport mode is introduced and/or traffic control is adjusted (e.g. bus lanes). Moreover, according to the Transportation Master Plan of Hanoi, the public transportation system in Hanoi by 2050 includes elevated metro, monorail, bus rapid transit and conventional bus [4]. Therefore, the suggestion of these five options is consistent.

As shown in Fig. 2, the modal share in mixed traffic environments is an important input of the mixed transport social cost model. The modal share for the existing situation (*base option*) is mentioned above while there are the following main assumptions for options 1-4. Firstly, the new modal share of the PT mode increases to 20%, compared to the modal share of the existing bus of 8.81%. The value of 20% is assumed because the main objective of the Hanoi transportation master plan is that the modal share of mass rapid transit (BRT, Monorail and Metro) would be between 15% and 20% by 2020, and 25%-30% by 2030 while the bus share would range from 20% to 25% [4]. Moreover, after investments in new PT technologies in Taipei, Taiwan, the share of mass rapid transit is around 19.7% accounting for half of the PT share [30]. Secondly, the ratio of the motorcycle share to the car share is unchanged, therefore, the modal shares of motorcycle and car in mixed lanes without PT are 67.96% and 12.04% of the total demand respectively. These values of modal shares are input into the mixed transport social cost model to estimate the ASC of each option for different demand levels.

In the social cost models, costs are estimated based on different currencies (e.g. Vietnamese currency and British currency) and different years. Therefore, all costs are converted to one currency in a based year by using a Purchasing Power Parity (PPP) rate and a discount rate. The PPP rate is defined as a price index that quantifies disparities in price levels across countries and enables the conversion of expenditures from national currencies to a common currency. Due to the variation in costs, including labour and materials, between the UK and Vietnam, the World Bank's Purchasing Power Parity (PPP) rate is used in this study. In 2015, the PPP rate for the UK stood at 0.69, while that rate for Vietnam was 7,576.25 [31]. Consequently, a conversion factor of 0.00009 (0.69/7,576.25) is utilised to convert Vietnamese currency to British currency.

5. Results

5.1. Basic results

To compare the ASCs of different mixed transport systems, the social cost models are calculated for the Nguyen Trai - Tran Phu - Quang Trung corridor. Fig. 4 shows the ASCs of five mixed transport options.

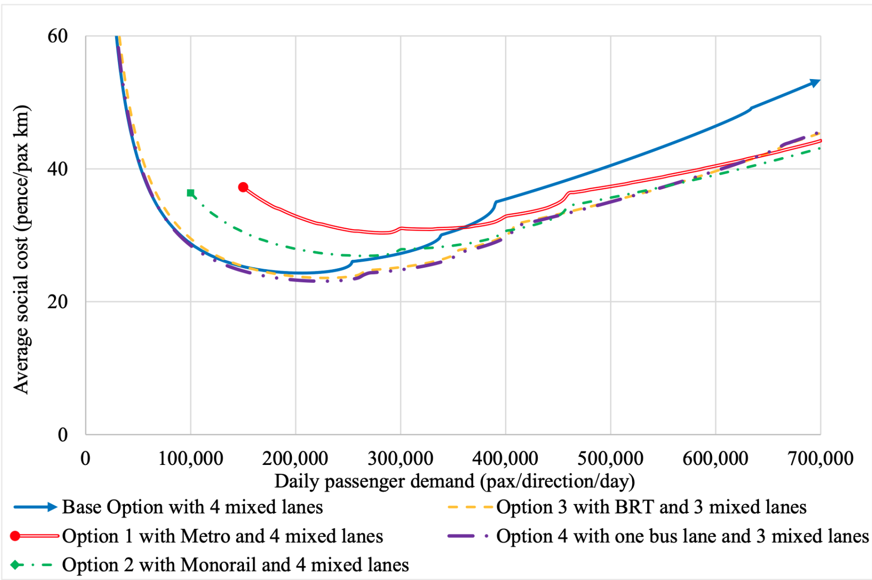


Figure 4. Average social costs of five mixed transport options, DR = 12%, 2015 prices

Fig. 4 describes that there are four kinks on each cost curve. These kinks appear at demand levels where traffic flow reaches infrastructure capacity, therefore, vehicle speeds decrease dramatically. As a result, the ASC increases considerably around these demand levels and critical speeds. Four kinks on each cost curve are relevant to four time periods of a day, which are shown in Table 6. For example, on the cost curve of the base option, a kink appears at a demand level of around 250,000 pdd at which the demand for the peak hour is 25,000 passengers/direction/hour. The traffic flow, which is converted to the motorcycle unit, reaches the capacity of 24,335 MCU/direction/hour. This value of capacity is shown in Table 1.

Fig. 4 shows that when the daily demand levels range from 15,000 to 300,000 pdd, the ASC of option 4 with exclusive bus lanes is the smallest. Moreover, the ASC of option 4 with exclusive bus lanes is only slightly lower than the ASC of the base option at low demand levels (less than 100,000 pdd). The reasons for those might be:

- At low demand levels, the speeds of car, bus and motorcycle are quite high and similar in all options because vehicles can move easily without hindrance by other vehicles or network objects.

- Infrastructure and vehicle capital costs of the base option and option 4 are very similar because one existing mixed lane is converted into one exclusive bus lane per direction for option 4. These costs for both options are lower than those costs of other options due to high operator costs of new PT modes (BRT, Monorail and elevated Metro).

Both option 3 with BRT and option 4 with exclusive bus lanes, which have very similar average social costs, are the best options when the daily demand is from 300,000 to 550,000 pdd. At these demand levels, options with rail-based technologies have still disadvantages due to great operator costs. When daily demand level is higher than 550,000 pdd, the ASC of option 2 with Monorail is the lowest. By assuming the modal share of PT accounts for 20% of the total demand, Monorail can attract more than 110,000 pdd (around the capacity of BRT), which makes option 2 with Monorail better than the options with bus-based technologies. The base option and option 1 with Metro cannot the best options with any study demand levels because of the following reasons. The speed of vehicles in the base option is lower than the speed of other options with the same demand level. Moreover, the operator costs of Metro is high while the number of Metro passengers is much less than the infrastructure capacity of around 512,000 pdd. For example, if the total demand is 700,000 pdd, the Metro passengers are assumed to be equal to 140,000 pdd.

As can be seen from Fig. 4, for comparisons between all options at the existing total demand of 407,700 pdd for the study corridor, options 1-4 are better than the base option in terms of ASC. As a result, in order to improve the performance of the current situation, transport planners and decision makers might consider these four options to analyse their feasibility and comparisons between them in a more detailed evaluation.

Sensitivity analysis is required to illustrate how the conclusions of comparative costs change. Because the external costs account for a small proportion of the total social costs for all options, a sensitivity test with respect to the external costs is not implemented in this study. This is consistent with the studies of [10]. The sensitivity tests with respect to the modal share of PT, the discount rate and value of time are conducted because these parameters can impact the operator costs and user costs, which account for large proportions of the total social costs for all options. These tests are described below.

5.2. Sensitivity test with respect to the discount rate

The sensitivity test with respect to the discount rate is carried out to analyse impacts on the comparative costs between different options. The base discount rate is 12%, therefore, the alternative values are 8% and 16%.

Fig. 4, Fig. 5 and Fig. 6 show the ASCs of five mixed transport options under three dissimilar DRs. Generally, when the DR increases from 8% to 16%, the cost curves of all options shift upward because infrastructure costs and capital vehicle costs rise. Moreover, the cost curves of option 1 with the more capital-intensive elevated Metro move upward at a faster rate than those of other options, in particular at low and medium demand levels. However, the mixed transport options having the lowest average social cost are broadly unchanged. Critical levels of demand levels, where the lowest ASC completely switches from the options with bus-based technologies to option 2 with Monorail, change with respect to the discount rate. These critical levels are at around 500,000; 550,000 and 590,000 pdd with respect to the DRs of 8%, 12% and 16% respectively. In summary, this sensitivity test illustrates that the basic results of the analysis are not substantially impacted by the DRs.

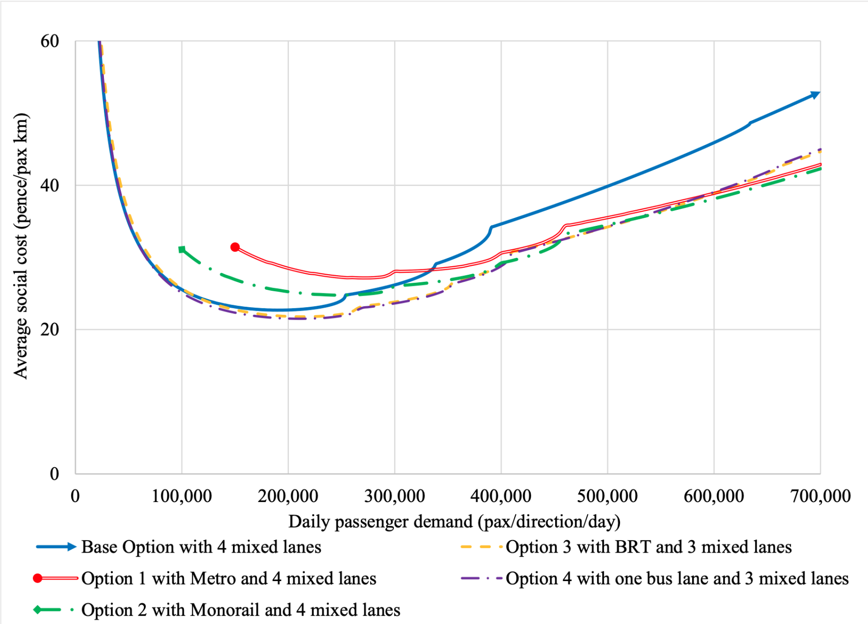


Figure 5. Average social costs of five mixed transport options, DR = 8%, 2015 prices

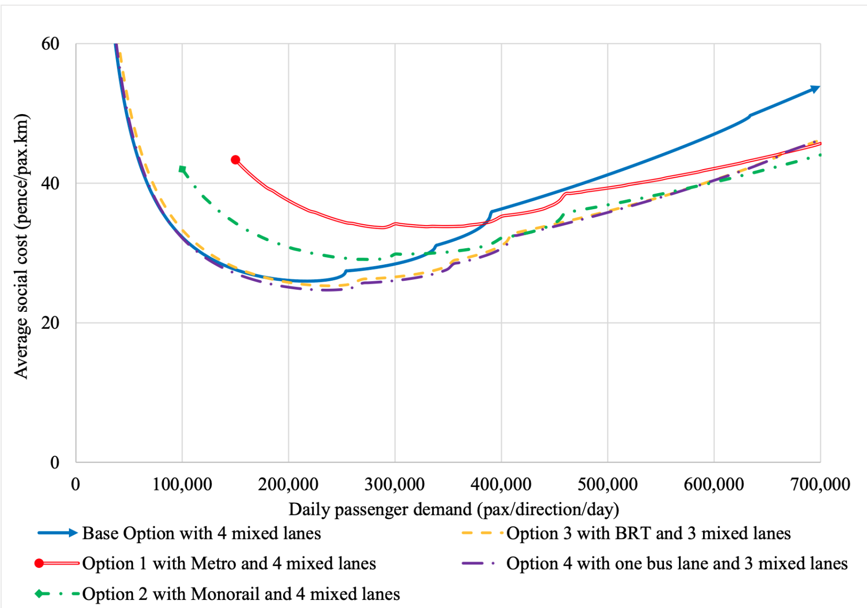


Figure 6. Average social costs of five mixed transport options, DR = 16%, 2015 prices

5.3. Sensitivity test with respect to the value of time

The sensitivity test with respect to the value of time (VoT) for different modes is conducted to analyse impacts on the comparative costs. Fig. 7 and Fig. 8 show the average social costs of five mixed transport options when the VoT decreases and increases by 25% respectively. In general, when the value of time increases, the cost curves of all mixed transport options shift upward due to increases in user costs. Additionally, the cost curves of the base option with higher private transport volumes shift upward at a faster rate than those of other options, especially at high demand levels causing congestion and very low speed. Similar to the sensitivity test with respect to the discount rate, there are no broad changes to the mixed transport options having the smallest average social cost for the range of demand levels studied. This means that the value of time does not importantly affect the basic results of the analysis.

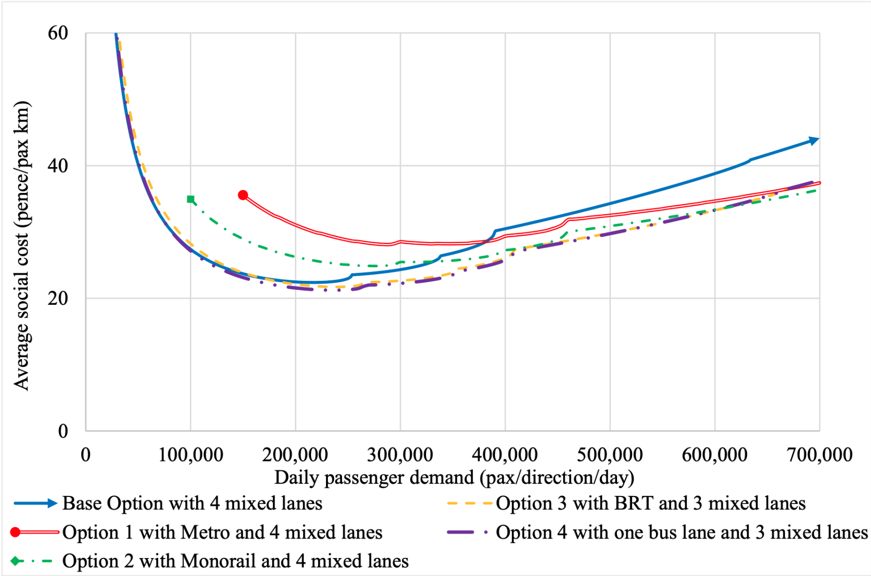


Figure 7. ASCs of five mixed transport options, the VoT decreases by 25%, 2015 prices

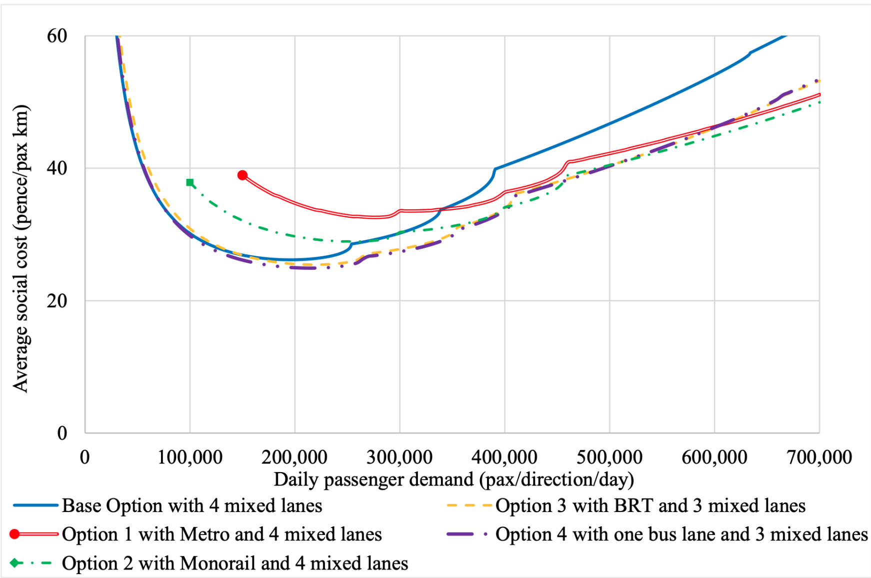


Figure 8. Average social costs of five mixed transport options, the VoT increases by 25%, 2015 prices

5.4. Sensitivity test with respect to the PT share

The sensitivity test with respect to the objective modal share of PT is conducted to analyse impacts on the comparative costs between different PT modes. The base PT share is 20% while the existing bus share is 8.81%. According to the aimed PT share in the Hanoi transportation master plan [4], the alternative values are assumed as 15% and 25%. Fig. 9 and Fig. 10 show the comparative costs for the PT share of 15% and 25% respectively. However, the PT share for one corridor or transport networks or a whole city can be set by decision makers in real local conditions. Different shares might be set for the different options in reality. Hence, based on the capacity of the PT modes, this research compares the five options when the share of bus-based technologies, Monorail and Metro are 15%, 20% and 25% correspondingly. These different shares for dissimilar PT modes are consistent with characteristics and comparisons of transit modes in the study of [32]. Fig. 11 illustrates the results of this comparison.

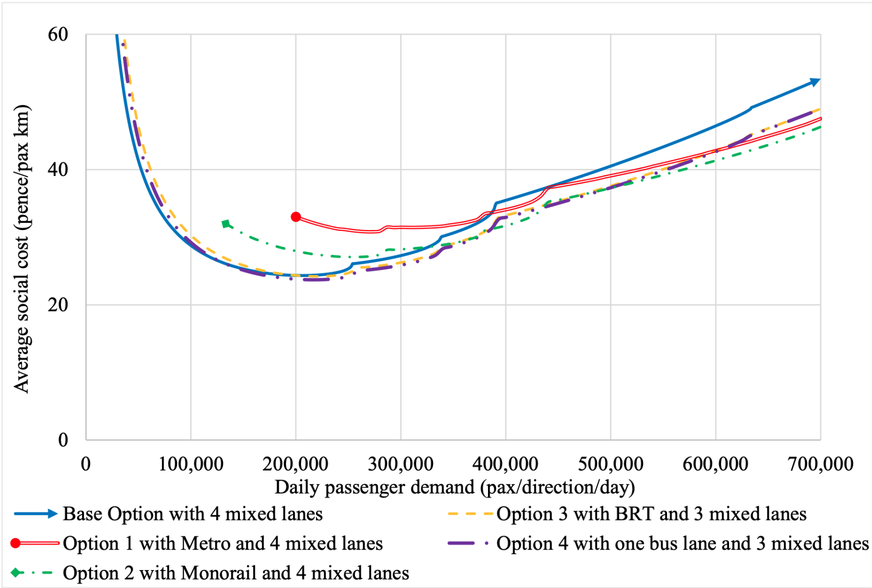


Figure 9. Average social costs of five mixed transport options, the PT share of 15%, 2015 prices

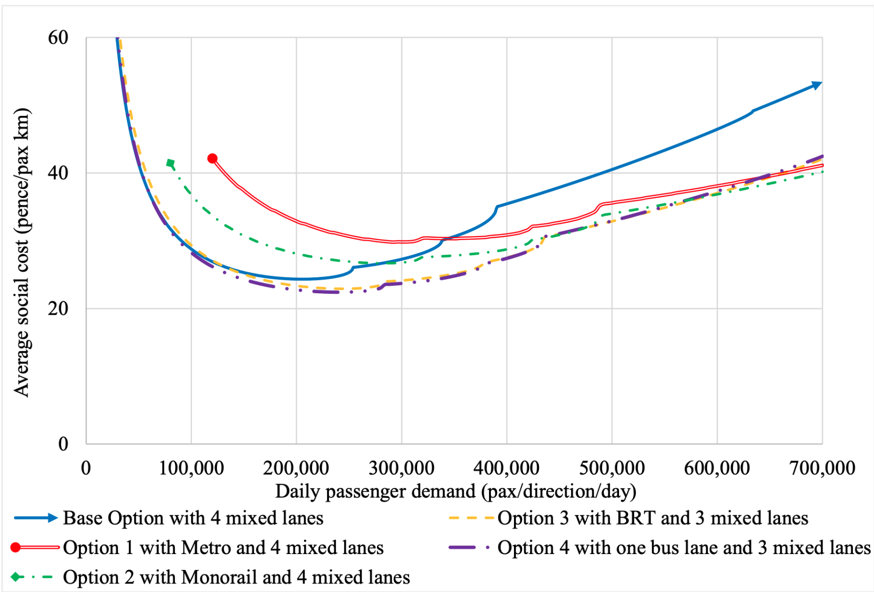


Figure 10. Average social costs of five mixed transport options, the PT share of 25%, 2015 prices

As can be seen from Fig. 4, Fig. 9 and Fig. 10, when the PT share increases from 15% to 25%, the cost curves of new mixed transport options shift upward because of the following reasons. Firstly, at the same total daily demand, smaller private transport demand causes lower user costs due to higher average speed. Secondly, the ASC of PT users seems to increase very slightly because PT demand is still much lower than infrastructure capacity.

PT share appears to be sensitive to comparisons between a new option and the existing situation at low demand levels. Fig. 9 shows that when the daily demand levels range from 15,000 to 150,000 pdd, the base option is better than new options in terms of ASC. On the contrary, when the daily demand is higher than around 390,000 pdd, all of new options are better than the base option. At the existing total demand of 407,700 pdd for the study corridor, the ASC of the existing situation is smaller than those numbers of any new options when the PT share ranges between 15% and 25%. It is suggested that at low levels of demand for a four-lane per direction corridor, low PT share are optimal whilst high PT share is optimal at high levels of demand.

Regarding comparisons between the new options with the same share (see Fig. 9 and Fig. 10), the option 1 with Metro has highest ASC with any study demand levels. Moreover, the new options having the lowest ASC are generally unchanged. Demand thresholds, where the lowest ASC completely switches from the options with bus-based technologies to the option 2 with Monorail, rise with respect to increases in the PT share. When the share of bus-based technologies, Monorail and Metro are 15%, 20% and 25% correspondingly, Fig. 11 shows the ASC of different options. The option 2 with Monorail has the smallest ASC when the daily demand is from 330,000 to 400,000 pdd while the option 1 with Metro has advantages at the daily demand level above 400,000 pdd. For the study corridor with the existing total demand of 407,700 pdd, the findings from this current study can help transport planners and decision makers in Hanoi to have a retrospective strategic evaluation of the Metro investment. Choosing the best choice in several PT modes would depend on demand-side impacts as endogenous demand would need to be considered in a detailed assessment.

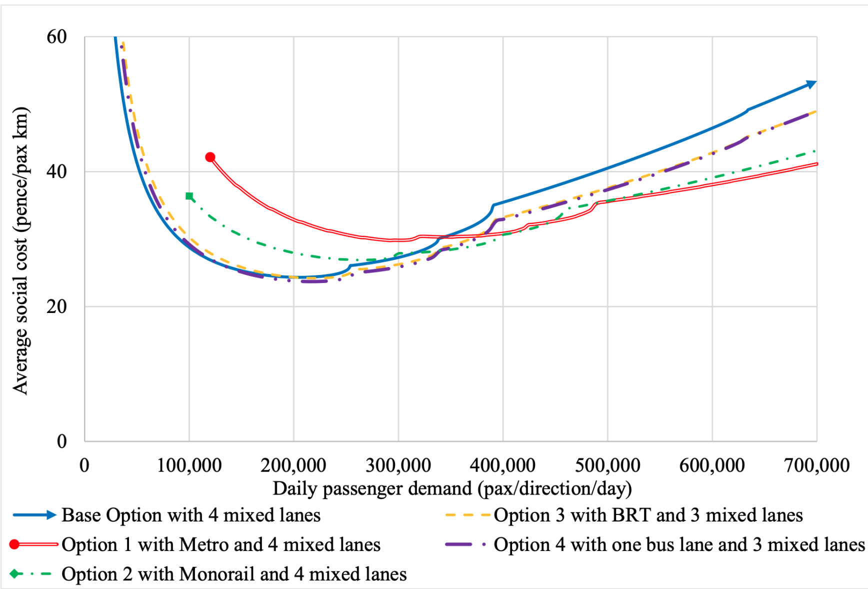


Figure 11. Average social costs of five mixed transport options with different shares, 2015 prices

6. Conclusions

This study introduces the social cost model for mixed transport based on the social cost models of public transport and private transport in the previous studies. The mixed transport social cost model is developed for a two-lane, three-lane or four-lane per direction corridor. Moreover, based on the flow-speed relationships in mixed transport with a dominance of motorcycles in [17], this research improves the flow-speed equation by using the Lambert W function to estimate the speed of mixed traffic corresponding to a given traffic flow. With optional inputs and the flexibility of the cost function, the social cost models are able to be modified to suit other local conditions where conventional bus, car and motorcycle share facilities and an innovative PT mode is introduced.

Transport planners and decision makers in cities, where motorcycles are dominant in mixed traffic, can draw the following from the Hanoi case study.

- For an existing four-lane per direction mixed traffic corridor with the dominance of motorcycles, any introduction of a new exclusive public transport (e.g. BRT, elevated Metro, Monorail) or conversion to exclusive bus lanes can be better than the existing situation when the modal share of PT increases from 8.81% to a range between 15% and 25%. It is recommended that any existing mixed traffic environments with medium and high demand levels can be improved by an introduction of a new PT mode or an exclusive bus lane at a strategic planning level.

- With the same PT passenger demand for all options accounting for 20% of the total daily demand, option 4 with exclusive bus lanes is cheapest at low and medium demand levels (less than 350,000 pdd). Option 3 with BRT and option 4 with exclusive bus lanes are the best options for daily demand levels ranging between 300,000 and 550,000 pdd. However, at the highest demand level (above around 550,000 pdd), the option with Monorail is the best alternative. This level of demand can be expected in 2025 if the annual growth rate of demand is around 4.5 %. This rate is estimated based on traffic volumes at the Le Trong Tan-Quang Trung junction on 10 May 2016 provided by the TTS group and the primary data of this current research collected on April 2018. If the mixed transport options with rail-based technologies attract more passengers than alternatives with bus-based technologies, the former has advantages at lower demand levels due to high person capacity. This is found in the comparisons of PT modes with different shares, which is illustrated in Fig. 11.

- For a given existing mixed traffic corridor with a specific demand level, potential PT modes can be suggested to analyse their feasibility in a more detailed assessment by using the mixed transport social cost model. This selection of potential PT modes at a strategic planning level might not only minimise the number of potential options for a detailed assessment but also avoid considering only one option for a detailed evaluation in certain situation.

However, it is also necessary to note the limitations of this study and then illustrate the future work that will deal with these limitations.

- Firstly, the main drawback of the mixed transport social cost model is that demand is exogenous. The mixed transport social cost model cannot estimate changes to the existing transport conditions when a new PT mode is introduced. Therefore, endogenous demand for all transport modes will be improved by using the demand elasticity with respect to a composite cost.

- Secondly, the modal share in the mixed transport system is assumed to be fixed. This model needs to incorporate incremental logit models to estimate preferences of users for alternative transport modes. Hence, PT shares would vary with the different technologies. This work will be reported in follow-up papers.

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Appendix A.

Table A.1. An example of calculating ASC of the existing situation with a demand of 407,700 passengers/direction/day

Section	Key parameters / short description	Values (round numbers up)	Notes
1. Basic parameters			
	Corridor length, *L* (km)	7	
	Journey length, *JL* (km)	4	
	Annualisation factor, *a* (day)	261	
2. Demand			
	Total daily demand, *D*	407,700	Unit is pax/direction/day.
	Demand for peak hour, D_1	40,770	Include morning and afternoon peak hour (pax/direction/hour).
	Demand for peak period, D_2	30,578	Include morning, afternoon and evening peak period (pax/direction/hour).
	Demand for mid-day off peak, D_3	26,500	pax/direction/hour.
	Demand for early morning and late evening off-peak, D_4	16,308	pax/direction/hour.
	Bus share, *b*	8.81 %	
	Car share, *c*	13.72 %	
	Motorcycle share, *m*	77.47 %	
3. Vehicle speed in peak hour			
	Bus demand, *bd*	3,592	$D_1 * b$ (pax/direction/hour).
	Bus occupancy, *bo*	33	
	Bus flow, *bf*	109	*bd/bo*
	Bus flow_MCU, *bf_MCU*	1,145	*bf_MCU = 10.5* bf*. One bus is equivalent to 10.5 MCU (Nguyen and Sano, 2012).
	Car demand, *cd*	5,593	$D_1 * c$ (pax/direction/hour).
	Car occupancy, *co*	1.57	
	Car flow, *cf*	3,562	*cd/co*
	Car flow_MCU, *cf_MCU*	12,111	*cf_MCU = 3.4* cf*. One bus is equivalent to 3.4 MCU [17].
	Motorcycle demand, *md*	31,585	$D_1 * m$ (pax/direction/hour).

Section	Key parameters / short description	Values (round numbers up)	Notes
	MC occupancy, *mo*	1.22	*md/mo*
	MC flow, *mf*	25,889	
	Total flow_MCU	39,145	*bf_MCU + cf_MCU + mf*
	The mean speed of motorcycle and car, *V_mean* km/h	7.58	Using the Lambert W function in Eq. (12).
	The mean speed of bus, *V_bus* km/h	6.68	
	Travel time per one trip by motorcycle or car, *TT_mc* (hour)	0.561	*TT_mc = JL / V_mean + 0.033.* Assume that travel time at intersections is 0.033 hours.
	In-vehicle time per one trip by bus, *TT_bus* (hour)	0.632	*TT_bus = JL / V_bus + 0.033.* Assume that travel time at intersections is 0.033 hours.
4. Productivity			
	Annual passenger-km for both direction, *PKM_all*	851,277,600	*PKM = 2 * D * JL * a*
	Annual motorcyclist-km for both directions, *PKM_MC*	659,484,756	*PKM_m = 2 * D * m * JL * a*
	Annual car passenger-km for both directions, *PKM_c*	116,795,287	*PKM_c = 2 * D * c * JL * a*
	Annual bus passenger-km for both directions, *PKM_b*	74,997,557	*PKM_b = 2 * D * b * JL * a*
5. Allocated infrastructure costs			
	Percentage of the total infrastructure cost allocated to bus, *pb*	7.37%	
	Percentage of the total infrastructure cost allocated to car, *pc*	31.75%	
	Percentage of the total infrastructure cost allocated to motorcycle, *pm*	60.88%	
	Annual total infrastructure cost, *TIC*	28,114,543 (£/year)	$CRF = r*(1+r)^m/((1+r)^m-1)$. *r* is DR, 12%. *m* is the life expectancy of infrastructure, 20 years. Annual infrastructure cost per km is the product of infrastructure cost per km and CRF.
6. Total social costs of motorcycle			
	6.1. Annual travel time costs. These are variable costs.	105,977,392 (£/year)	These costs are related to speed.
	6.2. Annual delay costs. The congested-related delay costs are variable costs.	45,070,838 (£/year)	Based on methods to estimate reliability from [33]. These costs are related to speed.
	6.3. Annual vehicle capital costs. These are variable costs, which are products of MC capital cost per MC-km and Annual MC-km.	20,811,608 (£/year)	Then MC capital cost is estimated as 0.0385 (£/MC-km).

Section	Key parameters / short description	Values (round numbers up)	Notes
	6.4. Annual operating costs. These are semi variable costs. Operating cost for 1 motorcycle in peak hour is calculated as 0.084 (PPP £/km).	10,757,902 (£/year)	Based on the relationship between MC operating costs and speed from the study of [27]. These costs, which are related to speed, are estimated for all periods of a day, then for the whole day.
	6.5. Annual maintenance costs. These are variable costs, which are products of maintenance cost per MC-km and Annual MC-km.	1,153,302 (£/year)	The MC maintenance cost is estimated as 0.213 (p/MC-km).
	6.6. Annual parking costs. These are fixed costs, which are products of average parking cost per MC-km and Annual MC-km.	5,675,892 (£/year)	The average parking cost is estimated as 1.05 (p/MC-km).
	6.7. Annual infrastructure costs allocated to motorcycle. These are fixed costs.	17,115,268 (£/year)	*TIC * pm*
	TUC_MC = (6.1) + (6.2) + (6.3) + (6.4)	219,889,382	Unit cost is £/year.
	TOC_MC = (6.5) + (6.6) + (6.7)	23,944,462	Unit cost is £/year.
	TEC_MC. These are variable costs, which are products of external unit costs and annual Passenger-km.	14,693,320	Unit cost is £/year. These costs include air pollution, noise pollution, climate change and accidents costs.
	TSC_MC = TUC_MC + TOC_MC + TEC_MC	221,255,522	Unit cost is £/year, in 2015 prices.
	*ASC_MC = TSC_MC*100 / PKM_MC*	33.55	Unit cost is p/pax-km, in 2015 prices.
7. Total social costs of car			
	7.1. Annual travel time costs. These are variable costs.	9,384,340 (£/year)	These costs are related to speed.
	7.2. Annual delay costs.	3,991,040 (£/year)	These costs are related to speed.
	7.3. Annual vehicle capital costs. These are variable costs.	11,202,676 (£/year)	Then car capital cost is estimated as 0.151 (£/car-km).
	7.4. Annual operating costs. These are semi variable costs. Operating cost for 1 car in peak hour is calculated as 0.367 (PPP £/km).	22,012,960 (£/year)	These costs are related to speed
	7.5. Annual maintenance costs.	158,752 (£/year)	The car maintenance cost is estimated as 0.213 (p/car-km).
	7.6. Annual parking costs. These are fixed costs.	2,291,270 (£/year)	The average parking cost is estimated as 3.08 (p/car-km).
	7.7. Annual infrastructure costs allocated to motorcycle. These are fixed costs.	8,926,120 (£/year)	*TIC * pc*
	TUC_car = (7.1) + (7.2) + (7.3) + (7.4)	52,670,736	Unit cost is £/year.

Section	Key parameters / short description	Values (round numbers up)	Notes
	TOC_car = (7.5) + (7.6) + (7.7)	11,376,142	Unit cost is £/year.
	TEC_car. These are variable costs.	389,160	Unit cost is £/year.
	TSC_car = TUC_car + TOC_car + TEC_car	58,356,318	Unit cost is £/year, in 2015 prices.
	*ASC_car = TSC_car*100/PKM_car*	49.96	Unit cost is p/pax-km, in 2015 prices.
8. Total social costs of bus			
	8.1. Annual user costs, *TUC_bus*. These costs include IVT, WKT and WTT. These are variable costs.	7,684,811 (£/year)	These costs are related to speed.
	Annual Vehicle Hours, *VH*	442,253	Based on required service frequency (*F*), speed (*V*) and *L*. *F* and *V* are calculated for all periods of a day. Time-related operating costs are variable costs.
	Annual Vehicle Distance, *VD*	3,860,168	Based on *F* and *L*. Distance-related operating costs are semi variable costs.
	Peak Vehicle Requirement, *PVR*. This is calculated for Period 1, that requires maximum vehicle.	244	PVR = CEILING(*bf*2*L/V_bus*(1+δ))*. CEILING() is a function to round up to integer values. δ is a factor allowing for spare vehicles, 10%. Vehicle-related operating costs are semi variable costs.
	Lane Distance, *LD*. Annual infrastructure costs allocated to bus	2,072,042	*TIC * pb*. Lane Distance costs are fixed costs.
	Number of Stop, *NoS*	28	*NoS = CEILING(L/ D_{Stop})*. The distance between stops is 0.5 km. Bus costs are fixed costs.
	Number of Depots, *NoD*	1	Depot costs are fixed costs.
	8.2. Annual operator costs, *TOC_bus*. The operator costs include vehicle operating and maintenance costs; and capital investment costs.	17,384,732 (£/year)	*TOC = ∑ (VH*unit cost_VH+VD*unit cost_VD+PVR*unit cost_PVR+LD +NoS*unit cost_ NoS+ NoD *unit cost_ NoD)*. Using default unit operator costs in Table 3.
	8.3. Annual external costs, *TEC_bus*. These are variable costs, which are products of external unit costs and annual Passenger-km.	124,345 (£/year)	These costs include air pollution, noise pollution, climate change and accidents costs. Using default unit external costs in Table 4.
	TSC_bus = TUC_bus + TOC_bus + TEC_bus	25,193,888	Unit cost is £/year, in 2015 prices.
	*ASC_bus = TSC_bus*100 / PKM_bus*	33.59	Unit cost is p/pax-km, in 2015 prices.
9. Total social costs of mixed transport			
	TSC_all = TSC_MC + TSC_car + TSC_bus	304,805,728	Unit cost is £/year, in 2015 prices.
10. Average social cost for all passengers			
	*ASC_all = TSC_all*100 / PKM_all*	35.81	Unit cost is p/pax-km, in 2015 prices.