A Comparative Economic Assessment of Urban Transport Infrastructure Options in Low- and Middle-Income Countries

Tam Vu[a,b,*] and John Preston[a]

[a]Transportation Research Group, Faculty of Engineering and Physical Sciences, University of Southampton, UK; [b]Faculty of Transportation Engineering, Hanoi University of Civil Engineering, Vietnam

*Corresponding author. Faculty of Transportation Engineering, Hanoi University of Civil Engineering, Hanoi, Vietnam; Email: tamvm@huce.edu.vn.

ORCID

Tam Vu https://orcid.org/0000-0003-1708-1647

John Preston https://orcid.org/0000-0002-6866-049X

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Abstract: Several innovative public transport (PT) projects have been developed in low- and middle-income countries (LMICs), where cars, motorcycles and buses share the facilities. However, there seems to be very little evidence on assessment methods to analyse the feasibility of different PT modes and identify the most cost-effective mixed transport system. To address this issue, this study develops a comparative economic assessment (CEcoA) based on the PT technologies' characteristics and the conditions of local transport networks. The assessment integrates four models. First, a social cost model (SCM), that calculates the social costs of each mode and mixed transport systems, is the key model in the assessment. Second, an incremental elasticity analysis (IEA) evaluates changes in total demand by using the demand elasticity with respect to a composite cost. The IEA solves the first drawback of the SCM that demand is assumed to be fixed. Third, an incremental logit model (ILM) estimates changes in modal shares with respect to generalised costs. The ILM overcomes the second disadvantage of the SCM, where preferences of users for all alternative transport modes are not considered. Fourth, a microscopic simulation model (MSM) simulates all existing transport modes' flows on the local network. The MSM solves the third drawback of the SCM, which only considers an isolated corridor without any interaction between the different modes and any junctions. The assessment was applied to compare an existing mixed transport situation and twelve options with an introduction of new PT technologies (Bus Rapid Transit - BRT, elevated Metro and Monorail) replacing the existing bus services; either wholly or partially, and with or without a congestion charge scheme for private transport (PRV) on a corridor in Hanoi, Vietnam in terms of average social cost (ASC), total demand and PT share. The results show that eight options with BRT or Monorail or Metro are feasible, whilst the BRT option that replaces all existing buses and includes congestion charging is the best alternative in terms of ASC. Transport planners and decision makers can draw on the findings of this research. A congestion charge scheme might be considered for the local conditions to meet specific objectives such as a reduction in ASCs and an increase in modal share of PT. The CEcoA can be a strategic tool for not only planning new PT technologies on corridors in the whole network but also retrospectively evaluating investments of PT modes. Moreover, the methodology of the CEcoA might be applied and modified to various transport networks with an abundance of motorcycles to assess the costs and benefits of new PT modes and mixed transport systems with or without the congestion charge.

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

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1. Introduction

The rapid development of urbanisation and modernisation has made a significant increase in demand for travelling in urban areas, in particular journeys by private vehicle (car and motorcycle) in low- and middle-income countries (LMICs).[1] Several PT projects (e.g. BRT, Metro and Monorail) have been invested in these nations such as Indonesia, Malaysia, Thailand and Vietnam (Government of Vietnam, 2016, Malaysia Economic Planning Unit, 2010). However, an important question is whether improving PT can lead to improvements in system efficiency given motorcycle dominance. Furthermore, when several PT modes are feasible, there seems to be very little evidence for transport planners and decision makers to determine the most cost-effective mixed transport system where transport modes share infrastructure facilities with the dominance of motorcycles, in terms of given criteria such as average cost per passenger, modal share of PT or increases in total demand. Hence, this study develops a comprehensive CEcoA of several mixed transport options with different PT technologies. The CEcoA can have advantages, compared to the combination of a four-stage transport model and cost benefit analysis (CBA) which is a popular approach for assessing transport projects in developing countries funded by the World Bank and Asian Development Bank (Asian Development Bank, 2017, World Bank, 2015a). The consistent CEcoA can be a useful strategic tool for transport planners and policy makers to prospectively plan new PT modes and to retrospectively assess investments of PT modes on corridors in the whole network. Furthermore, the CEcoA might evaluate some other transport policy interventions in conjunction with the introduction of the new PT mode in local conditions such as a congestion charge scheme. The structure of this paper is as follows. Section 2 reviews literature on evaluations of individual transport modes and mixed transport systems. Section 3 describes the methodological framework of this study to fill the gaps in the literature. Section 4

[1] As of 1st July, 2019, LMICs are defined as those with a Gross National Income per capita, calculated using the Atlas method, of US$ 12,375 or less in 2018 (World Bank, 2019).

introduces a case study in Hanoi, the capital of Vietnam. The key results of the CEcoA are presented in Section 5. Some conclusions and potential future work are discussed in Section 6.

2. Literature review

As summarised in the study of Preston (2021), the pioneering study of Meyer et al. (1965) compared costs of different modes including rail, bus and passenger car in different population densities (hence traffic density), in terms of average passenger trip cost. The social costs (TSCs) consisted of operator costs and user costs. Following this approach, Brand and Preston (2003) added the external costs to the social costs and initiated the Tools for Evaluating Strategically Integrated Public Transport (TEST) project, which developed a strategic evaluation tool for integrated PT. The prototype software helps users to explore the most appropriate PT technology (or technologies) for urban and short distance inter-urban corridors. The total social costs include operator cost, user cost and external cost. In the TEST project, a stand-alone model was developed to compare TSCs of different PT technologies (conventional bus, light rail and heavy rail system, and personal rapid transit) at a strategic planning level. In conjunction with the stand-alone model, an integrated model was also developed to evaluate alternative options in a case study of a guided bus system on a busy urban/inter-urban corridor in Oxfordshire, UK. Based on the study of Brand and Preston (2003), Li and Preston (2015) assessed total socials costs of PT modes with respect to endogenous demand by revising the speed-flow and waiting time equations. Furthermore, Li (2015) developed a completed assessment integrated by a cost model, a binary mode choice logit model, incremental elasticity analysis and microscopic simulation model to compare the existing conventional bus service with a conceptually innovative public transport technology, Straddle Bus, on Minzu Avenue in Nanning, China, in terms of social cost, average social cost and passenger demand level. The cost model calculates the social costs of public transport modes. The binary mode choice logit model evaluates the competition between travelling by car and PT (bus or Straddle Bus). The incremental elasticity analysis estimates change PT demand by using the demand elasticity with respect to generalised PT passenger journey time. The microscopic simulation model simulates a network including cars and buses. The completed assessment was run for the existing situation and a proposed situation where Straddle Bus replaces all existing bus service on the corridor. The result showed Straddle Bus was better than the existing bus services in terms of average social cost and passenger demand.

Similarly, bus rapid transit, light rail and heavy rail transit on a radial network in Australian cities were compared by minimising the total costs (operator and user costs) (Tirachini et al., 2010). The frequency and number of PT lines, which not only impact walking time, waiting and in-vehicle time but also affect the total operator costs, were considered for the optimisation of the total costs. Furthermore, Grimaldi et al. (2010) developed a stylised cost benefit analysis model to evaluate the choice between conventional bus and upgrading towards a light rail transit (LRT) in an urban corridor where different bus services superpose their routes while having different paths in the outskirts. The LRT is upgraded on the corridor where existing bus lines overlap. Grimaldi et al. (2010) evaluated the total costs and benefits of the two options (existing bus services and a new LRT) in terms of Net Present Value. Moreover, Avenali et al. (2020) compared the social economic costs of bus and rail in Italy to support the Italian local policy makers in re-programming the local public transport services with more efficiently the financial public funds. The social economic costs cover standard costs (operation, fleet maintenance, administration, and the pre-tax cost of capital), infrastructure usage costs, user costs and external costs. At the beginning of the model, demand behaviour of the transport service on a single binary origin-destination path is analysed with different levels of exogenous demand. At the end of the model, the less socially expensive transport mode is suggested to be switched in re-programming current services.

For comparisons between private transport and public transport, Jakob et al. (2006) compared the total costs of passenger car and bus including the external and internal costs in Auckland, New Zealand. The external costs cover accident costs, air pollution cost and climate change cost. The internal costs are directly spent by the government to run the transport system. The vehicle capital cost and other costs such as congested-related delay costs were not considered in that study. In addition, seven transport modes (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 are compared in terms of average cost per passenger-km (Wang, 2011). The average cost for each mode is estimated by dividing the full costs (capital, operation, user time, safety and environmental costs) by traffic volumes. Additionally, Vu and Preston (2020) developed a social cost model for eight transport modes (passenger car, motorcycle, Taxi, Uber, conventional bus, BRT, elevated Metro and Monorail) on an urban corridor in Hanoi, Vietnam. The total social costs covered operator, user and external costs and these eight modes were compared in terms of ASC.

In general, these previous studies focused on the comparative costs of single transport modes for fixed demand levels, except the study of Li and Preston (2015) which considered endogenous demand for PT modes but not for mixed transport. Moreover, there seems to be very little evidence on economic assessments of different mixed traffic options where new PT technologies (e.g. BRT, Metro, Monorail) are introduced. To fill the gaps in the literature, this study therefore extends the existing literature in two respects. Firstly, a social cost model with endogenous demand for mixed transport including PRV (car and motorcycle) and PT (existing bus and a new PT mode), which has not previously been considered in the literature, is developed. Secondly, this research creates a CEcoA for evaluating the feasibility of a new PT mode (BRT, Monorail or elevated Metro) and choosing the most cost-effective mixed transport system in a detailed assessment, in terms of average social cost. Average social cost is a form of cost effectiveness analysis. Cost effectiveness analysis might be appropriate situations where there are several potential mixed transport options with different new PT modes. The reason is that this method helps simplify the analysis compared to a comprehensive cost-benefit analysis, especially across a range of transport modes. Furthermore, treating PT fares as a transfer also simplifies the analysis although the demand models need to make assumptions about fares. This has advantages in generalising the analysis in that pricing is context-specific but has practical limitations when proffering design guidance for local public transport systems. In such cases, comprehensive cost-benefit analysis can provide more detailed tactical assessment to supplement the strategic cost effectiveness analysis.

3. Methodology

A Social Cost Model (SCM), an Incremental Elasticity Analysis (IEA), an Incremental Multinomial/Nested Logit Model (ILM) and a Microscopic Simulation Model (MSM) are developed for the first stage. These four models are then integrated into a comparative economic assessment for one urban corridor.

3.1. Social cost models

This research uses the social cost model of single modes for one urban corridor in the study by Vu and Preston (2020) and the social cost model for mixed transport in Vu and Preston (2022). In the SCM of individual PRV or PT modes, it was assumed that only one mode uses the infrastructure facility for fixed daily demand that is the sum of the demand for peak and off-peak periods. The total social costs (*TSC*) of each transport mode consist of total operator costs - *TOC* (or infrastructure operator costs for PRV), total user costs – *TUC* (vehicle user cost for PRV) and total external costs (*TEC*) (Brand and Preston, 2003, Small and Verhoef, 2007). The mixed transport social cost model included passenger car, motorcycle, bus and an innovative PT mode. The TSCs of mixed transport cover the TSCs of PT and PRV and are relatively straightforward to compute, except for the shared infrastructure costs. The methodology of the mixed transport social cost model is detailed in Appendix A. The total social costs and demand levels are estimated in the first place. The average social cost of a mixed transport option is then estimated as:

$$ASC_{all} = \frac{TSC_{all}}{PKM_{all}} \quad (1)$$

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.

3.2. Traffic microscopic simulation model

The traffic microscopic simulation model simulates all existing transport modes' flows on a mixed corridor to obtain traffic data such as operating speed and travel time. Among several microscopic simulation packages such as AIMSUN, SUMO, PARAMICS, FLOWSIM and VISSIM, VISSIM is chosen for the assessment because this software is suitable for the context of the current study, which focuses on motorcycle dominated mixed traffic.

The development of the VISSIM model includes the data collection process, the creation of the VISSIM simulation model and the calibration and validation process. Firstly, data must be collected for the study corridor in both peak and off-peak periods. The data include traffic volume data at junctions, data on bus, data on signals at junctions, infrastructure geometry and data on vehicle travel time. The local acceleration parameters of motorcycle should be collected, analysed and inserted directly in VISSIM because the acceleration default values are for typical motorcycles used in Europe. Secondly, collected data on infrastructure geometry, signalised control data and traffic data are inserted in VISSIM to develop the simulation models for the peak and off-peak periods. Then, the calibration and validation process is conducted by using the nine-step procedure by Park and Schneeberger (2003).

In the calibration and validation processes, the first step is to determine the key performance indicators as the measures of effectiveness. The travel time of motorcycle, car and bus are chosen as key performance indicators because these indicators are important in not only the simulation model but also in the social cost models and incremental demand models. In addition, these indicators can be collected from the VISSIM simulation model and from the field to test the accuracy. Another important step is to choose calibration parameters in VISSIM. As the VISSIM model simulates the mixed transport system with motorcycle, the local acceleration parameter of motorcycle was collected, analysed and inserted directly in VISSIM without calibration. Four calibration parameters in VISSIM are chosen as (i) desired speed of car and bus; (ii) desired speed of motorcycle; (iii) minimum lateral distance driving when overtaking vehicles on the same lane; and (iv) average standstill distance. A linear regression model is built in the SPSS program with the four calibration parameters as the independent variables and the vehicle travel time as the dependent variable (Park and Schneeberger, 2003, Li, 2015). Based on a significance level of 5%, these four parameters have significant impacts on the travel time of bus, car and motorcycle. This proves that choosing the four parameters is consistent and acceptable. Another key step is to identify the best parameter set that provides a close match with the field performance indicators while the last step is the validation process of the best parameter set. Two different sets of data on vehicle travel time are used for the model calibration and the model validation. The best parameter set is determined by using one set of data collected on-site. The validation process is conducted to test the accuracy of the parameter sets by comparing the outputs of the VISSIM simulation and another set of vehicle travel times collected on-site. Two statistical tests are performed in the calibration and validation process to test the reliability of the simulation model. Firstly, the independent two-tailed Student's t-test is run to see if the means of vehicle travel times obtained from the field observation and the simulation are equal. Secondly, the Kolmogorov-Smirnov test is used to evaluate the goodness-of-fit of the two probability distributions of vehicle travel times. The results of these statistical tests proved that the VISSIM simulation models are sufficiently reliable to represent the real mixed traffic with a dominance of motorcycles. The chosen calibration parameter sets for the VISSIM models of peak and off-peak periods are described in Table *1*.

Table 1: Chosen calibration parameter sets for the simulation models

Period	Average standstill distance (m)	Minimum lateral distance driving (m)	Desired speed distribution of bus and car (km/h)	Motorcycle desired speed distribution (km/h)
Off-peak	0.5	1.0	50	50
Peak	0.5	0.8	40	40

3.3. Incremental elasticity analysis

When the existing transport condition on an urban corridor changes, the IEA estimates endogenous changes in the total demand by using the demand elasticity with respect to a logsum. Balcombe et al. (2004) stated the elasticities with respect to generalised costs that include PT fare, in-vehicle time, walking time and waiting times. The generalised costs elasticities range between -0.4 and -1.7 for buses, -0.4 and -1.85 for London Underground, and -0.6 and -2.0 for national railways. Additionally, Wardman and Toner (2020) estimated generalised cost elasticity of around -2.0 for long-distance rail travel in London, based on annual data from 1995 to 2005. Moreover, Lee (2000) estimated the elasticity of car travel with respect to total price, which consists of fuel cost, tolls, parking fees, vehicle wear and travel time. The results showed the generalised cost elasticities are from -0.5 to -1.0 in the short-term, and from -1.0 to -2.0 in the long-term. In general, those studies illustrated that the generalised cost elasticities are different for different modes and ranges between -0.4 and -2.0. To simplify the analysis in this current study focusing on passenger car, bus, motorcycle and new PT modes, it is assumed that the demand elasticity with respect to utility is equal to -1.0. The change in per cent in the total demand (Q) is therefore estimated as:

$$\frac{\Delta Q}{Q} = \frac{Ln\,(e^{Ucar_1}+e^{Umc_1}+e^{U_{PT_1}}) - Ln\,(e^{Ucar\_0}+e^{Umc\_0}+e^{Ubus\_0})}{Ln\,(e^{Ucar\_0}+e^{Umc\_0}+e^{Ubus\_0})} \quad (2)$$

where,

U_{car_0}, U_{mc_0}, U_{bus_0} are the utilities of car, motorcycle and bus in the before situation respectively;

U_{car_1}, U_{mc_1}, U_{PT_1} are the utilities of car, motorcycle and PT in the after situation correspondingly. If a new PT mode is introduced to operate with the existing bus service, the PT utility is for composite alternatives including the existing bus and the new PT mode.

3.4. Incremental logit models

When the existing transport condition changes, the IEA cannot evaluate changes in modal shares. Hence, the ILM might solve this issue. A new PT mode (e.g. BRT, Metro or Monorail) is introduced to replace either all or partial existing bus services on one mixed traffic corridor where bus, car and motorcycle share infrastructure facilities. This can depend on local regulated or deregulated environments, therefore two Scenarios are considered in this research. For Scenario 1, if the new PT technology replaces all bus services running on the partial and whole corridor, these bus routes can be adjusted to not overlap the new PT route in reality. Therefore, they become feeder systems that transport passengers to new PT stations/stops. This means that the new PT mode is run exclusively whilst car and motorcycle share a mixed traffic environment. The incremental multinomial logit model is used for Scenario 1 and the probability of choosing each mode is calculated using an equation based on the Department for Transport (2017b). For Scenario 2, if the new PT mode replaces only bus services running on the whole corridor, existing bus services running on segments of the corridor are still operated. The incremental nested logit model is used for Scenario 2. The upper nest includes motorcycle, car and PT while the existing bus and the new PT mode are included in the lower nest of PT. The probabilities of choosing each mode at each nest are calculated based on the equations for incremental nested logit models in the studies by Preston (1991) and the Department for Transport (2017b).

3.5. Methodological framework

The structure of the CEcoA is shown in Figure 1. The four models mentioned above would be closely interacting with each other to compare mixed transport systems with the introduction of a new PT mode and a transport policy in terms of ASC, modal share of PT and total demand. Therefore, the SCM is the key model in the completed assessment. However, the SCM has some drawbacks needed to be solved. The MSM can overcome the first drawback of the SCM, which only considers an isolated corridor without any interaction between dissimilar modes and any junctions. The IEA might solve the second drawback of the SCM that demand is assumed to be fixed. The ILM can overcome the third disadvantage of the SCM, where preferences of users for all alternative transport modes are not taken into account. Hence, these four models are integrated into one comprehensive assessment, in which one iteration shows the connection between these models and displays how each model works.

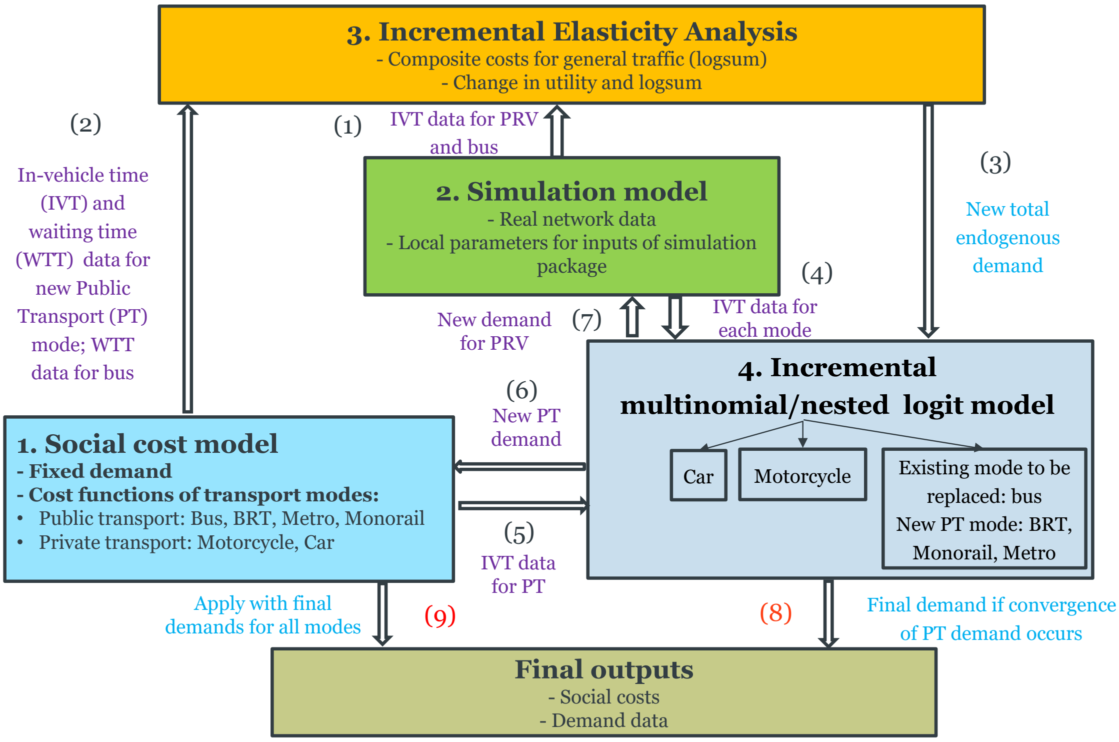

Figure 1 Operating procedure of comparative economic assessment

The CEcoA begins with providing an existing mixed transport corridor, as well as an introduction of a new PT technology and a transport policy on the corridor. The MSM simulating the existing mixed transport network and the SCM evaluating in-vehicle time (IVT) and waiting time (WTT) of new PT users provide required data (travel time, operating speed, etc.) for the IEA to estimate changes in total demand of all transport modes. The required data obtained from the MSM and SCM; and the new endogenous demand from the IEA are inputted to the ILM to estimate new modal shares and demand levels of each transport mode. These new demand levels are used as inputs for the MSM and the SCM for the next iteration of the CEcoA. The iterations are implemented until the convergence is reached when the difference between the previous PT passenger demand and current PT passenger demand is less than 1%. The iterations are run in Python, which interfaces externally with VISSIM. Final outputs will be produced from the SCM to show the total TSCs and ASC of each transport mode and mixed transport systems on the corridor. Hence, the feasible options will be analysed and the best one will be then identified.

4. Case study

Hanoi, the capital of Vietnam, is a good case study for this research because of the following reasons. Firstly, Vietnam is determined as a lower middle income country with a gross national income per capita of US$ 2,400 in 2018 (World Bank, 2019). Secondly, the characteristics of the transport system in Hanoi can represent many cities in LMICs, where motorcycles are dominant, for example, Malaysia (Hussain et al., 2011), Indonesia (Sugiyanto et al., 2011) and Thailand (Satiennam et al., 2011). Thirdly, in conjunction with existing conventional bus systems, several new PT projects have been invested in Hanoi such as BRT and urban rail transit (Government of Vietnam, 2016). The Nguyen Trai - Tran Phu - Quang Trung (NT-TP-QT) corridor with a length of 7.0 km, which is a four-lane per direction major arterial in Hanoi, is selected for the CEcoA because an elevated Metro service has been operated on this corridor since 2021 (Government of Vietnam, 2016).

The next subsection describes the basic input parameters of the CEcoA. The data collection process is illustrated in the second subsection. The last subsection introduces a congestion charge scheme for PRV, which can be considered in conjunction with an introduction of a new PT technology to achieve a significant shift from PRV to PT.

4.1. Basic input parameters

The basic input parameters in the SCM are used from the study of Vu and Preston (2020). This current research considers three existing transport modes (conventional bus, car and motorcycle) and three new PT modes (BRT, elevated Metro and Monorail). The characteristics, default unit capital costs and life expectancies of these modes are shown in Table 2. Table 3 illustrates the unit PT operator costs. The default external unit costs by the six modes are described in Table 4. Table 5 shows passenger demand split into different times of the day.

Table 2 Vehicle characteristics, default unit capital costs and life expectancies

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

Source: Vu and Preston (2020)

Notes:

All costs are in 2015 prices. The discount rate (DR) for capital investment is set at 12% (World Bank, 2015a).

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		

Source: Vu and Preston (2020)

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

Transport modes	Air pollution (p/pax km)	Noise pollution (p/pax km)	Climate change (p/pax km)	Accidents cost (p/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

Source: Vu and Preston (2020)

Table 5 Passenger demand split into different times in the Hanoi case study

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%

Source: Vu and Preston (2020)

There is little empirical evidence on the utility function parameters of car, motorcycle, bus and other public transport (e.g. Metro or BRT), especially in Vietnamese cities. Bray and Holyoak (2015) and the Economic and Policy Services Pty Ltd. (2014) studied travel behaviour in Hanoi, Vietnam by establishing a discrete choice modelling framework with the ability to represent mode choice. The mode choice survey established statistically valid explanations of the quantitative factors that impact the discrete choice decision to use a motorcycle, car, motorcycle taxi, existing bus or proposed rapid transit modes (e.g. Urban Railway Transit or BRT). The survey was carried out between April and June 2014, and attracted a total of 6,047 responses. Then 5,993 complete records were distributed for both routine trips (e.g. work or education) and non-routine trips (e.g. shopping or recreation). Utility function parameters in multinomial logit models were therefore estimated for routine and non-routine trips by using the application of the NLOGIT software. These parameters can be used in the current work because of the following reasons. Firstly, the estimation of the utility parameters was achieved after a low number of iterations for the maximum likelihood estimation convergence. Model significance reported in the NLOGIT output (Prob [chi squared > value]) = 0.0000 was achieved by all model estimations in that study. As this chi squared estimate is less than a level of significance of 0.05, the model parameter estimates are judged to be reliable for all models. Secondly, compared to the observed choices made in the survey, the aggregate percentage of correct predictions was approaching 60% for all mode choice models for both routine and non-routine trips (actual range 56.4% to 58.9%). Given the presence of five modes, this indicates that the mode choice models produced in that study have reasonable accuracy, considering the number of alternatives and attributes for each presented in the choice structure. Thirdly, the vast majority (around 80%) of the estimated utility function parameter values were statistically significant at the 5% level.

The modal share of routine and non-routine trips in Hanoi was shown in the study of the Japan International Cooperation Agency (2007). Based on the modal share data in this study and the utility function parameters in the study of Bray and Holyoak (2015), the average coefficients of utilities for the Hanoi case study are estimated in order to simplify the analysis of the current research. These coefficients are shown in Table 6.

Table 6 Utility function parameters for the Hanoi case study, 2014 values

	Mode Specific Constant (MSC)	Travel time	Walk time	Wait time	Fuel cost	PT fare
Motorcycle	1.6303476	-0.0100492			-0.0002116	
Car	1.3253908	-0.0045308			-0.0001628	
Bus	0.6655476	-0.0051492	-0.011216	-0.011216		-0.0146
New PT	0.9961844	-0.0044962	-0.011216	-0.011216		-0.0146

Based on Japan International Cooperation Agency (2007) and Bray and Holyoak (2015)

Notes: The units of the time, fuel cost and PT fare in the utility functions are minutes, Vietnamese currency (VND)/km and VND/1,000 respectively. The MSCs of the four modes above whilst the MSC of motorcycle taxi is equal to zero. The wait time coefficient is assumed to be the same as the walk time coefficient.

Table 6 shows that the MSCs of new PT modes are smaller than those numbers for PRV in this study. The reason is that the utility functions are adapted from the surveys in the study by Bray and Holyoak (2015) that were carried out in 2014 when the performance of only PT mode (bus) seemed to be quite poor. In a different study by Satiennam et al. (2011), the results showed students preferred to travel by motorcycle rather than bus. That study developed the logit model to forecast the mode choice behaviour between motorcycle and campus bus for home-based education trip purpose at the Khon Kaen University, in the North East of Thailand, where the motorcycle share is 75%.

The values of time for different modes are estimated based on the utility coefficients in Table 6. The values of time for different modes in PPP £/hour in 2015 prices are transferred over location and time by using Purchasing Power Parity (PPP) rate from Vietnam to the UK (World Bank, 2015b) and an increase in income over time with an elasticity of 1.0 (Department for Transport, 2017a). The results of the values of time for the Hanoi case study are shown in Table 7.

Table 7 Value of in-vehicle time for different modes for the Hanoi case study

Modes	Coefficient of IVT	Coefficient of fuel cost	Coefficient of PT fare	Value of time (VND/hour), 2014 prices	Value of time (PPP £/hour), 2015 prices
Motorcycle	-0.0100	-0.00021		20,516	1.92
Car	-0.0045	-0.00016		12,023	1.12
Bus	-0.0051		-0.0146	21,091	1.97
New PT	-0.0045		-0.0146	18,415	1.72

Source: adapted from Bray and Holyoak (2015)

In the study of Vu and Preston (2020), the values of time for car, motorcycle and PT are estimated as £0.77, £1.54 and £0.54 per hour in 2015 prices respectively. For the values of time for motorcycle and car, the differences between the study of Vu and Preston (2020) and this current study are not significantly high. However, compared to the values of time for PRV, the values of in-vehicle time for both existing conventional bus and proposed PT technology seem to be higher. The reason for that can relate to characteristics of the existing bus systems during survey time in 2014 when new PT modes (e.g. BRT and Metro) were not operated. Bray and Holyoak (2015) stated that Hanoi citizens were concerned about the bus system, which includes safety and personal security, over-crowding, service reliability and air conditioning. Similarly, Molt (2016) and Vu (2015) showed that there were poor bus services in Hanoi around that time. These factors can lead to increases in the value of in-vehicle time for bus passengers (Litman, 2020). However, most of Hanoi's citizens with the lowest income chose bus and/or bicycle for cost saving reasons (Vu, 2015). This will impact on the VoT of bus travel. Hence, the reduced VoT for new PT modes should be considered and is shown in subsection 5.2.

4.2. Data collection

The data collection process was implemented on the NT-TP-QT corridor from February to June 2018 by the first author and around 100 surveyors. Firstly, traffic volumes at ten junctions on the corridor were collected from 16:30 to 18:30 on Monday 16 April 2018. One group of surveyors at each junction recorded all movements of vehicles by using cameras. The video recordings were extracted to count the traffic volume of each mode for each movement (turn left, turn right and go straight) in-house. The results show that the shares of conventional bus, car and motorcycle are dominant whilst other modes (e.g. bicycle, truck etc.) account for a minority of traffic volumes. Therefore, only bus, car and motorcycle are considered as the existing modes and their shares of bus, car and motorcycle on the corridor are 8.81%, 13.72% and 77.47% respectively. Additionally, based on the daily demand split into different times shown in Table 5, the daily demand for this corridor is estimated as 407,700 pdd.

Secondly, the Hanoi Police Department (HPD) manages cameras in real time at two junctions on the corridor. Video recordings at these junctions (7:00-9:00, 12:00-13:00 and 17:00-19:00) on Monday 19 March and Thursday 22 March 2018 were provided by the HPD. The traffic volumes for the off-peak period were counted in-house by using video recordings provided by the HPD.

Thirdly, surveys at thirty bus stops on the whole corridor were conducted from 16:30 to 18:30 on Thursday 19 April 2018. The types of data collected for all bus services running on the corridor include: (i) number of boardings and alightings; (ii) bus occupancy; (iii) arrival/departure time and stopping time; and (iv) boarding/alighting time per passenger.

Fourthly, motorcycle acceleration surveys were carried out by using the Stalker ATS II radar gun, which traces and records speeds of observed vehicles. Samples of 200 motorcycles were obtained at different speeds ranging from 0 km/h to a speed limit of 50 km/h on the corridor. Long (2000) suggested that the linearly decreasing model of acceleration related to speed of travel performs well in terms of both maximum vehicle acceleration and normal motorist-chosen acceleration, for both cars and trucks. Using recorded data on speed and time from the Stalker ATS II radar gun, a correlation coefficient and equation of the fitted line are determined for each motorcycle for each speed band of 5-km/h. The results show that the speed-time relationship is a linear function because all sample correction coefficients are higher than 0.85. Hence, the local acceleration parameters of motorcycle are estimated as the slope of the linear function line, and are then inserted directly in VISSIM. Appendix B shows the detailed estimation of motorcycle acceleration parameters.

Fifthly, other types of data including signalised data at intersections and infrastructure geometry were collected for developing the VISSIM simulation model. The VISSIM package with student version 6.0 is able to simulate a maximum corridor of 1.5 km. Hence, a segment with a length of 1.5 km including three junctions on the study corridor is simulated in VISSIM.

Finally, travel times of bus, car and motorcycle on the selected segment are chosen as key performance indicators in the calibration and validation process. Firstly, travel time of conventional bus between two given points (bus stops) on the segment was collected for both directions from 15:00 to 19:00 on 17 May 2018. Two surveyors at a stop counted manually information including bus service number, bus plate number and bus arrival/departure time. This set of data is different from the set of data collected on 19 April 2018. Additionally, travel time of conventional bus can be determined from video recordings provided by the HPD when bus service number and time recorded can be identified. These data are used for the off-peak period. Secondly, to collect travel time of cars between two given points on the segment, one surveyor and one author drove a car between the two points on different weekdays during the collection data period. A sample of 100 cars was carried out in one direction for the period from 16:30 to 17:30 and another sample of 100 cars was implemented in the opposite direction for the period from 17:30 to 18:30. For the calibration and validation process, these are two different sets of data in terms of time periods and directions. Thirdly, to collect travel time of motorcycles between two given points on the segment, ten surveyors including the author rode motorcycles of two people between the two points on different weekdays during the collection data period. A sample of 200 motorcycles was carried in one direction for the period from 16:30 to 17:30 and another sample of 200 motorcycles was in the opposite direction for the period from 17:30 to 18:30.

4.3. Congestion charge for private transport

According to the report of the Hanoi Department of Transport (2021), the congestion charge is proposed to be introduced in central areas in Hanoi from 2025 but the estimation of the congestion charge is not yet identified. Therefore, the marginal congestion cost (MCC), which is estimated in this study, relates to the change in travel time and operating costs for users. For one corridor, the MCC in £/vehicle-km can be calculated as (Link et al., 2016, Santos and Shaffer, 2004, Walters, 1961):

$$MCC = -E_S . \frac{V}{S} \tag{3}$$

where,

E_S is the elasticity of speed with respect to traffic;

V is the value of time and additional operating costs (£/vehicle-hour);

S is speed (km/hour).

The MCCs for cars and motorcycles are estimated separately. For each transport mode, the MCCs for the peak and off-peak periods are calculated individually as the VISSIM models were developed for both periods. In order to estimate the MCC for cars, the VISSIM model simulates four scenarios with increases of 10% and 20%; and decreases of 10% and 20% in the total car volumes, compared to the existing car volumes. The motorcycle and bus volumes are assumed to be unchanged, however, these modes still impose congestion on cars in the VISSIM simulations. The average travel time and speed of cars are obtained from the VISSIM simulations and then compared to existing values to calculate elasticities of car speed with respect to traffic. Based on the collected data in subsection 4.2, the VISSIM simulation models identify the existing average motorcycle and car speeds, travel times of motorcycle and car between two given points are obtained from the VISSIM simulation models. Four scenarios with changes in the car volumes are simulated in VISSIM in order to obtain the vehicle speeds.

The average demand elasticities of speed, which is a mean of four values for the four scenarios, is then used for calculations of the marginal congestion costs. Similarly, for the calculation of the MCC for motorcycles, the VISSIM model simulates four scenarios with rises of 2% and 3%; and reductions of 2% and 3% in the total motorcycle volumes, compared to the existing motorcycle volumes because the existing motorcycle volumes are around seven times as high as the existing car volumes. Table 8 and Table 9 shows the results of the MCC for cars and motorcycle correspondingly.

Table 8 The results of the MCC for cars in pence/car-km in 2015 prices

	Car volumes decrease by 20%	Car volumes decrease by 10%	Car volumes increase by 10%	Car volumes increase by 20%	Average MCC
Peak	9.6	14.9	12.6	8.5	11.4
Off-peak	0.2	0.1	0.9	0.9	0.5

Table 9 The results of the MCC for motorcycles in pence/motorcycle-km in 2015 prices

	Motorcycle volumes decrease by 3%	Motorcycle volumes decrease by 2%	Motorcycle volumes increase by 2%	Motorcycle volumes increase by 3%	Average MCC
Peak	55	44	19	30	37
Off-peak	3	3	7	5	5

Table 8 and Table 9 show that the MCCs for motorcycles are higher than those for cars. The first reason can be that the value of time for motorcycles is greater than that for cars. Secondly, the motorcycle speed seems to be more sensitive than the car speed with respect to traffic as motorcycles are dominant in the existing mixed traffic situation. However, the congestion charge for cars can be suggested for both modes for the Hanoi case study to ensure that the charge cannot be a regressive tax on middle-income and poor people. A regressive tax is defined as where a tax takes a higher share of the income of low-income people than of high-income people (Santos and Shaffer, 2004). Vu (2015) carried out a survey with 800 Hanoi citizens in 2012 about household vehicle ownership and mode choice preferences. The results of that study showed that the poorest mainly use bus and bicycle, the lower-middle-income and upper-middle-income people choose motorcycles while high-income individuals use cars. As a result, in order to minimise regressive effects, charges based on estimated MCCs of £0.114/vehicle-km and £0.005/vehicle-km are applied for the PRV users in the peak and off-peak period correspondingly. Using the PPP rate, the congestion charge for the peak and off-peak periods are estimated as 1,250.7 and 56.74 VND/ vehicle-km respectively. The congestion charge affects demand in the IEA and ILM but it is not included in the total social cost calculation as it is a transfer between road users and road operators.

The utility functions of motorcycle and car for the Hanoi case study, which are shown in Table 6, include only fuel cost in terms of cost. Hence, the congestion charge coefficients to be included in the utility functions need to be determined. The methods for estimating the congestion charge coefficients include: (i) development of equations for the elasticity of PRV demand with respect to fuel cost and congestion charge based on the logit model formulation and (ii) transferability of evidence from the London congestion charge scheme to the Hanoi case study. Firstly, based on the existing modal shares, fuel price and fuel cost coefficient value for the Hanoi case study, the elasticity of car demand with respect to fuel price is estimated as -0.175, which seems to be consistent with the literature as Goodwin et al. (2004) reviewed the effects of fuel price on traffic levels and showed that the elasticity of car demand with respect to fuel price is -0.16 for the short-term estimation. Secondly, Santos (2004) studied the London Congestion Charge Scheme and showed the elasticity of car demand with respect to the generalised cost is -2.5. A congestion charge of £5 was a component of the average generalised cost of £23 per car trip. This can imply the elasticity of car demand with respect to the congestion charge in London is around -0.54. Assuming this value of -0.54 is assumed to be used for the Hanoi case study, the congestion charge coefficient in the car utility is estimated as -0.000501. Thirdly, the elasticity of car demand with respect to congestion charge is about three times (0.54/0.175) as high as the elasticity of car demand with respect to fuel price for the Hanoi case study. The factor of (0.54/0.175) is assumed to be applied to motorcycles. The elasticity of motorcycle demand with respect to fuel price is estimated as -0.036, therefore, the elasticity of motorcycle demand with respect to congestion charge for the Hanoi case study is calculated as -0.1111. The congestion charge coefficient in the motorcycle utility is then estimated as -0.000393.

5. Results and discussion

5.1. Analysis of feasible and best options

For the existing corridor in Hanoi, 12 options are proposed, which consider three PT modes (BRT, Monorail and elevated Metro), replacements of all or partial existing bus services (Scenarios 1 and 2), and a congestion charge scheme (with or without). To analyse the feasibility of these options and identify the most cost-effective mixed transport system, the ASC, total demand and PT share of all options are produced and then shown in Figure 2. Appendix C shows an example calculation for the Metro option for Scenario 2 with the congestion charge scheme for the peak period.

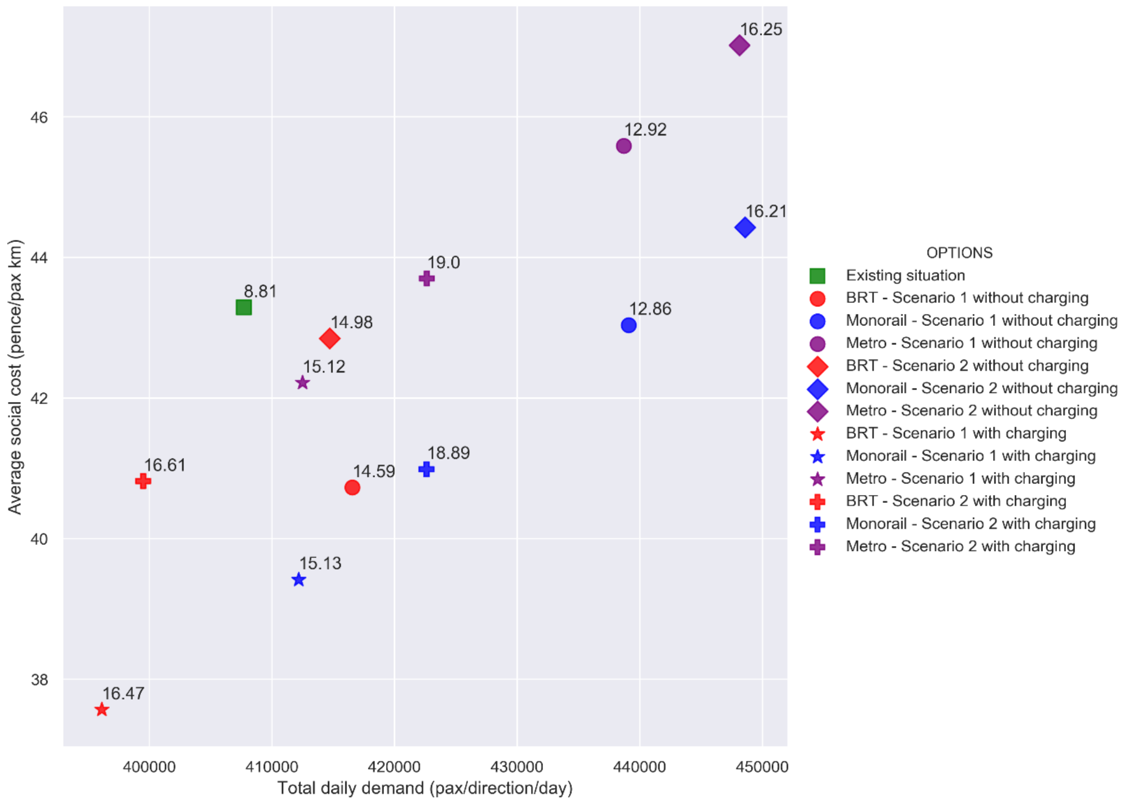

Figure 2 ASCs, total daily demand and PT share of all options, a discount rate of 12%, 2015 prices

Notes for Figure 2:

- One marker presenting for one option is plotted based on the total daily demand and the ASC of the option while a label number above the marker shows the PT share for this option.

- The BRT, Monorail and Metro options are shown in red, blue and purple markers respectively.

- Circle markers show options of Scenario 1 without the congestion charge scheme.

- Diamond markers show options of Scenario 2 without the congestion charge scheme.

- Star markers show options of Scenario 1 with the congestion charge scheme.

- Plus markers show options of Scenario 2 with the congestion charge scheme.

Figure 2 shows the following key findings.

- Two comparisons among the options of the three new PT modes are shown below. Firstly, the ASCs of the BRT options are the smallest whilst the elevated Metro options have the greatest ASCs. This can be explained that the introduction of Monorail or elevated Metro attracts approximately between 45,000 pdd and 70,000 pdd respectively, which are much lower than their infrastructure capacity of around 255,000 for Monorail and 512,000 pdd for Metro. Therefore, the ASCs of the Metro and Monorail options are still great, especially the Metro options with the highest operator costs. By contrast, the daily BRT demands for all options are around half of the BRT capacity, which is 109,000 pdd. Secondly, the total demands of the corridor after the introduction of Monorail or elevated Metro are similar but higher than those numbers for the BRT options. The main reason is that a median mixed traffic lane is converted to be a dedicated BRT lane per direction while PRV users have more spaces in the same current number of mixed traffic lanes when the existing bus is partially or completely replaced by Metro or Monorail. To summarise, the Monorail or elevated Metro demands are considerably lower than their infrastructure capacity although the frequency of the new PT mode reaches the infrastructure capacity. Hence, a sensitivity test with respect to the MSCs of all transport modes must be conducted for further work because the MSCs of new PT modes are smaller than those numbers for PRV. The reason is that the utility functions are adapted from the surveys in the study by Bray and Holyoak (2015) that were carried out in 2014 when the performance of only PT mode (bus) seemed to be quite poor.

- Two comparisons between Scenario 1 with circle and star markers and Scenario 2 with diamond and plus markers are drawn. First, the ASCs of the options with Scenario 2 are higher than those numbers of the options with Scenario 1. Compared to the options with Scenario 1, the PT shares for the options with Scenario 2 are higher but the new PT demand is smaller because the partial existing bus services still share the facility with PRV. The smaller new PT mode demand can cause the higher ASCs due to the high operator costs of the new PT mode. Second, the total demand for the corridor for Scenario 2 is greater than that for Scenario 1. The exception is the BRT option without the congestion charge scheme. This can prove that operating both a new segregated PT mode and existing bus service can be more competitive and attractive than PRV.

- Both the total demand for the corridor and the ASCs of the options with the congestion charge scheme are lower than those values for the options without charging. For the comparison of the total demand, the congestion charge leads to dramatic decreases in car and motorcycle demand, as well as significant shifts from PRV to PT. For example, the PT share for the Monorail option with the congestion charge is around 18.9%, compared to 8.8% for the existing situation. Compared to the options without charging, the higher PT demand and the smaller PRV demand for the options with charging result in the lower ASCs. To summarise, the congestion charge scheme leads to lower ASCs and higher PT share for all options. This charging scheme also causes the higher demand for the Monorail and Metro options. As a result, the transport planners and decision makers should consider the congestion charge scheme for the local conditions to meet specific objectives such as a reduction in ASCs and an increase in modal share of PT. Moreover, those people might introduce environmental charge (based on Pigou's polluter pays principle) costs as well as the congestion charge for PRV to attract more Metro or Monorail passengers to avoid wasteful investments.

- When decision makers set the ASC, total demand and PT share as the multi-criteria for analysing the feasibility of each option, a feasible option will have a smaller ASC, a higher total demand and a higher PT share compared to the existing situation. There are six such options: the Monorail options for Scenario 1 with and without charging, the Monorail option for Scenario 2 with charging, the BRT options without charging for Scenario 1 and Scenario 2 and the Metro option for Scenario 1 with charging. Among these six options, decision makers might select the Monorail option for Scenario 2 with charging because this option has two advantages of two of the three criteria in relative terms in pairwise comparisons.

- To compare with the existing situation in terms of ASC, eight options including the Monorail options for Scenario 1 with and without charging, the Monorail option for Scenario 2 with charging, the Metro option for Scenario 1 with charging and all four BRT options are better. Interestingly, five of six options with charging are feasible except the Metro option for Scenario 2 with charging. Among these eight feasible options, the BRT option for Scenario 1 with charging has the smallest ASC of 37.57 pence/pax-km. However, the total demand for this option decreases by around 12,000 pdd, compared to the existing situation. This decrease is caused by the congestion charging scheme. To conclude, the BRT option for Scenario 1 with charging is the best of the options considered in the CEcoA of this study if minimising ASC is the sole objective.

The detailed results of the best option show several significant improvements in performance and cost when the BRT service is operated on the NT-TP-QT corridor to replace all existing bus services. Firstly, in terms of performance, there are increases in the total daily demand, PT demand, modal share of PT and speed of PT. The daily BRT demand reaches 65,241 ppd, over half of the BRT capacity, compared to 35,918 bus passengers per direction per day in the existing situation. Secondly, the TSCs and ASC decrease by 16% and 13% respectively while the average generalised time cost for PT users and PRV users reduce by 57% and 6% correspondingly. The reductions in the average generalised time costs are resulted from increases in vehicle speed, in particular in PT speed in the peak period.

5.2. Sensitivity test with respect to the value of time

A sensitivity test with respect to the value of in-vehicle time for users of new PT modes is implemented because of the following reasons. Firstly, the user costs account for a main portion of the TSCs. Secondly, the value of time (VoT) can impact on results of the incremental demand models due to change in the utility. Thirdly, the VoT for the Hanoi case study is based on the study by Bray and Holyoak (2015). The surveys in that study were carried out when no new PT mode was operated. Fourthly, a new PT technology can provide better comfort, safety and service reliability etc. This can be reflected in lower IVT parameter in the utility functions. Hence, the reduced VoT should only be in the after situation whilst the increased VoT is not considered. The baseline estimate of the VoT for new PT modes (in 2015 prices) is shown in Table 7. The alternative value is equal to 50% of the baseline value to ensure that the alternative value for PT users is smaller than the VoT for cars. That is why a factor of 25%, which is suggested by the Department for Transport (2017a), is not used for this research. Assuming that PT fares are unchanged, the coefficients of in-vehicle time in the PT utility functions decrease by 50%. Furthermore, the coefficients in the utilities for car and motorcycle remained unchanged but the values of car and motorcycle utilities still vary due to changes in travel time and fuel cost. The results of the sensitivity test show that the changes in the ASC of the twelve options are higher than the changes in the total demand and PT share. Figure 3 shows the changes in the ASC in the sensitivity test.

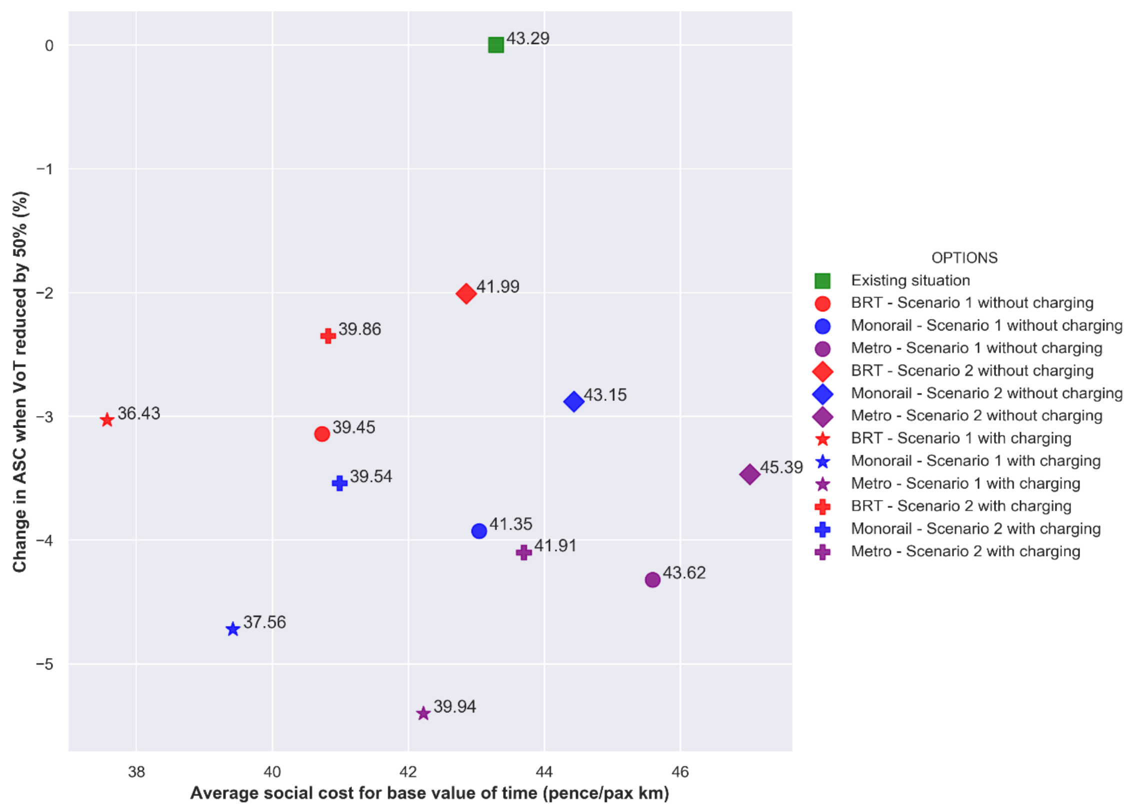

Figure 3 Changes in the average social cost for different options when the value of time for new PT users reduced by 50%, compared to the ASCs with the base VoT

Notes:

- One marker presenting for one option is plotted based on the change in the ASC when the VoT reduced by 50% and the ASC of this option with the base VoT while a label number above the marker shows the ASC of this option when the VoT reduced by 50%.

- The BRT, Monorail and Metro options are shown in red, blue and purple markers respectively.

- Circle markers show options of Scenario 1 without the congestion charge scheme.

- Diamond markers show options of Scenario 2 without the congestion charge scheme.

- Star markers show options of Scenario 1 with the congestion charge scheme.

- Plus markers show options of Scenario 2 with the congestion charge scheme.

Figure 3 shows that the ASC of twelve options appear to be only slightly sensitive with respect to the VoT for new PT modes because decreases in the ASC of twelve options range from 2% to 5% when the VoT declined by 50%. The reason can be that the total new PT user costs account for between around 30% and 50% of the total new PT social costs and the IVT costs are equal to around 20%-30% of the total user costs at forecasted demand levels. Additionally, the new PT share of between approximately 13.15% and 19.15% for all options, which is not great, cannot make the ASC be sensitive with respect to the VoT for new PT users.

However, the comparison of the ASC between one proposed option and the existing situation are sensitive with respect to the VoT for new PT modes in that a key threshold may be crossed. Two of the four options, which have higher ASCs than the existing situation, have smaller ASCs than the existing situation when the VoT reduced by 50%. In other words, these two options, which are the Monorail for Scenario 2 without charging and the Metro for Scenario 2 with charging, become feasible in terms of ASC. However, the BRT option for Scenario 1 with charging is still the best option in terms of minimising ASC.

6. Conclusions

The main contribution of this study is to develop the comprehensive methodology of the CEcoA to analyse the feasibility of a new PT mode and/or a congestion charge scheme and identify the best mixed transport system with an abundance of motorcycles, in terms of ASC, modal share of PT and total general traffic. The CEcoA is integrated from the social cost model, VISSIM simulation model, incremental elasticity analysis and incremental logit models. The CEcoA is then applied to the NT-TP-QT corridor in Hanoi, Vietnam for a detailed assessment of urban transport infrastructure options. Firstly, the CEcoA evaluates the social costs, including the operator, user and external costs for both private transport and public transport (Vu and Preston, 2020), as well as mixed transport (Vu and Preston, 2022). Secondly, this assessment simulates the interactions between all vehicles in a mixed traffic environment with an abundance of motorcycles by using the VISSIM simulation models. The results of the model calibration and validation process prove that the VISSIM simulation models are sufficiently reliable to represent the real mixed traffic. Thirdly, this assessment forecasts the endogenous growth of the total demand for the mixed traffic corridor and the changes in demand for each transport mode when the existing conditions change. Fourth, the assessment is run through the interface between VISSIM and Python. The CEcoA can be a strategic tool for not only planning new PT technologies on corridors in the whole network but also retrospectively evaluating investments of PT modes.

An alternative to the methodology of this study is to run a four-stage transport model and a CBA, which is one popular approach for assessing transport projects in developing countries funded by the World Bank and Asian Development Bank (Asian Development Bank, 2017, World Bank, 2015a). Compared to this macro-level working procedure, the CEcoA has the following advantages. Firstly, since the four-stage transport model is used to forecast transport demand for the whole network if a new PT mode is introduced, a huge amount of traffic data for the whole network is required to be collected for this model, whilst only traffic data on the study corridor is required in the CEcoA. Secondly, a main issue of the four-stage model is the consistent use of variables affecting demand such as travel time. For example, at the end of the traffic assignment stage, the new traffic volumes are produced and new travel times will be obtained. These might be different from travel times assumed when the distribution and mode choice models were run. Hence, the distribution and modal-split models need to be re-run based now on the new travel times, and can therefore lead to an unstable set of distribution, modal split and assignment models with consistent travel times (Ortuzar and Willumsen, 2011). This problem is overcome in the assessment of the current study because the CEcoA integrates from the social cost model, microscopic simulation model, incremental elasticity analysis and incremental multinomial/nested logit model and is run automatically in Python to achieve a convergence of PT demand and supply after several iterations. Thirdly, as there are several PT modes such as conventional bus, BRT, Monorail and Metro, as well as PRV including car and motorcycle, it can be difficult to estimate modal shifts between these multiple PT and PRV modes in the conventional four-stage model whilst the CEcoA can forecast modal shifts between PT and PRV. For example, the MVA Hong Kong Limited and SYSTRA S.A (2020) used the four-stage model to forecast travel demand for two scenarios with and without the introduction of the first BRT line in Ho Chi Minh city, Vietnam. The results of the macroscopic traffic simulation model showed the total demand for each transport mode for the whole network in 2025, 2030 and 2035, as well as the BRT demand on the corridor. However, modal shifts between BRT and other modes on the corridor could not be estimated.

The key findings from the Hanoi case study can be drawn below.

Firstly, a congestion charge scheme, which is introduced in conjunction with a new PT technology, leads to a lower ASC and a higher PT share.

Secondly, compared to the options replacing all existing bus services, the options replacing partial existing bus services have advantages in terms of total daily demand and PT share but have higher ASCs.

Thirdly, for a four lanes per direction corridor with the dominance of motorcycles, the ASCs of the BRT options are the lowest whilst the elevated Metro options have the highest ASCs due to high operator costs.

Lastly, the BRT option with a charging scheme replacing all existing bus services, which is the most cost-effective option, has several significant improvements in performance and cost compared to the existing situation. These include smaller TSCs, a lower ASC and a higher total daily demand as well as a significant increase in PT demand and speed.

The methodology of the CEcoA can be applied and modified to various motorcycle dominated mixed transport networks to analyse the feasibility of a new PT mode or a transport policy, as well as the most cost-effective mixed transport option. The default parameters in these models can be able to be modified to suit other local conditions while data on traffic volumes, infrastructure and signalised control in the traffic simulation need to be updated for those contexts. Moreover, the VISSIM models are developed in this research to simulate a mixed transport network where small and medium-sized motorcycles are dominant compared with cars and buses. The desired acceleration default value in VISSIM, which is for typical motorcycles used in Europe, should be replaced by local acceleration characteristics of motorcycles. Four calibrated parameters in VISSIM, which are validated on the Hanoi case study, might be used for other contexts.

It is necessary to note the limitations of this study and then illustrate the future work.

First, for the options with Monorail and elevated Metro, the demands for these modes are considerably lower than their infrastructure capacity at which the frequency reaches. Hence, a sensitivity test with respect to the MSCs of all transport modes must be conducted for further work because the MSCs of new PT modes are the same and smaller than those numbers for PRV in this study. Ben-Akiva and Morikawa (2002) estimated the relative attraction of bus and rail relative to the car modes, which is measured by the coefficients of the dummy variables representing the mode specific constants. Those authors concluded that the Metro service in the Washington DC area attracts more ridership than a bus service with comparable travel times and costs. In addition, a high quality express bus service with exclusive right-of-way may be equally attractive as the Metro service. Furthermore, Scherer (2010) used cognitive approaches to understand the preferences of light rail to bus transit. Four main factors for higher ridership attraction for light rail included capacity of light rail vehicles (load factor); qualitative factors of reliability and comfort; individual perception about transit (modern vehicles, special design, visibility of route and media presence). These factors need to be included in demand models through the MSCs. Hensher and Rose (2007) showed that the MSCs of PT modes are higher than those for cars. Those authors introduced state-of-the-art stated choice designs to parameterise modal choice models for commuting and non-commuting travel futures in the introduction of new public transport infrastructure in the north-west section of metropolitan Sydney such as new heavy rail, light rail and segregated busway systems. A two-level nested logit model with a competition between car and all PT modes is run for both work trip and non-work trip segments. Furthermore, a crowding function can be included in further work in order to evaluate the attractiveness of Metro. Another limitation is that external factors (e.g. land-use changes) are not considered in this research.

Second, the VISSIM model simulates a segment with a length of 1.5 km due to the limit of the student version of the VISSIM package. After traffic flows on this segment are obtained from the VISSIM model, demand for the whole corridor is estimated by using a proportionate factor. This factor is estimated based on the collected data on the corridor. Future research will develop a VISSIM model for the whole corridor.

Third, after the CEcoA is run for the off-peak and peak periods separately, the daily demand is the sum of the demands for the off-peak and peak periods. This means that demand shift between different periods of the day is not considered. Hence, the additional work needs to consider that the utility of peak travel may be affected by the time and costs of off-peak travel and vice versa. Moreover, this work does not consider the impact of Covid-19 on demand levels on the study corridor.

Fourth, this study shows that the introduction of both a congestion charge scheme and a new PT mode leads to an increase in the modal share of PT. Hence, considering air pollution and climate change charge for PRV is a potential additional work to evaluate impacts of these charges. These environmental charges might be a solution to attract more existing PRV users to use PT.

Fifth, because transport projects seem to be sensitive to capital costs and forecasted demand (Asian Development Bank, 2013), future research will conduct sensitivity tests with respect to the discount rate, infrastructure costs and demand elasticity with respect to a composite cost. Additionally, wider economic and social benefits should be included because these factors can change the results of the ASC of each option.

Finally, the assessment does not include other transport modes in urban areas such as bicycle, electric bicycle, electric motorcycle, taxi-motorcycle, Taxi and Uber. Therefore, those transport modes must be considered for future work. The ILM needs to expand more levels and nests or a cross-nested logit model should be considered.

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Appendix A

The methodology of the mixed transport social cost model in the study by Vu and Preston (2022) is detailed below.

The total social costs of a mixed transport system consist of the total social costs of public transport and private transport. However, the infrastructure costs of the segregated public transport mode (e.g. Metro and Monorail) and the infrastructure costs of mixed lane facilities are calculated separately. The infrastructure costs of the mixed lane facilities are allocated to transport technologies (e.g. car, motorcycle and conventional bus). Assuming that eighty-five per cent of the infrastructure costs reflect the capacity needs in terms of different types of vehicles, which are converted to passenger car units (PCU). Fifteen per cent of the infrastructure costs are related to heavy duty vehicles in particular that reflect increased road damage. These costs are allocated in terms of gross weight vehicle-km (Bruzelius, 2004). The allocation of the mixed lanes infrastructure costs is estimated in Equation A.1 (Sansom et al., 2001).

$$\sigma_i = 0.85 * \frac{\delta_i * APVKT_i}{\sum \delta_i * APVKT_i} + 0.15 * \frac{GMWPV_i * APVKT_i}{\sum GMWPV_i * APVKT_i} \quad \text{(A.1)}$$

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 (Transport for London, 2010). In a motorcycle dominated transport network, a bus and a car are equivalent to 10.5 and 3.4 motorcycle equivalent units (MCU) correspondingly (Nguyen and Sano, 2012); These MCUs 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 (Chu et al., 2005, Nguyen et al., 2007, Nguyen and Sano, 2012). To convert other transport modes into Dynamic Motorcycle Unit (MCU) by using a formula as follows:

$$MCU_i = \frac{V_{mc}/V_i}{S_{mc}/S_i} \quad \text{(A.2)}$$

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.

The study developed an application to determine the speed of mixed traffic with a dominance of motorcycles corresponding to a given traffic flow (or passenger demand). The application was based on the flow-speed relationships expressed as an exponential function by Nguyen and Sano (2012) and the Lambert W function (Biswas et al., 2017). Nguyen and Sano (2012) developed a MCU model and then showed the flow-speed relationships and capacity for three types of urban mixed traffic corridors (see Table A.1).

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

	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 Equation 1)	11.3	11.2	12.3
Capacity (MCU/direction/hour)	24,335	21,725	13,358

Source: Nguyen and Sano (2012)

Based on the speed equations of Small (1983), Brand and Preston (2003), Nguyen and Sano (2012), Li (2015) and Biswas et al. (2017), the mean stream speed of all modes on a mixed traffic corridor is estimated as:

$$V_{mean} = \begin{cases} min\left[-c * lambertW\left(-1, -\frac{q}{k_j c}\right), V_{max}\right] & if\ q \leq C \\ \frac{L}{\frac{L}{v_0} + \frac{1}{2} * W * \left(\frac{q}{C} - 1\right)} & if\ q > C \end{cases} \quad (A.2)$$

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 obtained for a particular roadway;

q is the all mixed traffic flow (MCU/direction/h). One bus and one car are converted into 10.5 and 3.4 MCU respectively (Nguyen and Sano, 2012);

V_{max} is the maximum operating speed (km/h). This can be the speed limit on the corridor;

C is the highway capacity (MCU/direction/hour), which are shown in Table A.1;

L is the length of the corridor (km);

W is the peak period duration in hours. In this study, the default value is 1 hour;

Lambert W function is run in the MATLAB program.

The motorcycle and car speeds are estimated as V_{mean} in Equation A.2 while the speed of bus in mixed traffic is estimated as:

$$V_{bus} = \frac{V_{mean}*A*D_{stop}*1000}{\left(\frac{V_{mean}}{3.6}\right)^2+A*\left(D_{stop}*1000+T_{dwell}*\frac{V_{mean}}{3.6}\right)} \tag{A.3}$$

Appendix B

There are six steps for estimating motorcycle acceleration for each speed band, which include: (i) observed motorcycles were selected for one speed band; (ii) for the raw data of each motorcycle from the Stalker ATS II, biased points, which show speeds of other vehicles nearby the objective vehicle, need to be eliminated; (iii) speed-time values for each vehicle from the Stalker ATS II are exported to an Excel file; (iv) a linear model is made for speed-time relationship for each observed motorcycle where a correlation coefficient and equation of the fitted line are determined for this motorcycle; (v) if the speed-time linear model appears to be consistent, the acceleration of each observed vehicle can be calculated from the slope of the fitted line; and (vi) Maximum, minimum and median values of acceleration are determined for each speed increment. To minimise impacts of outliers, an approach is to use a five per cent trimmed median, where the five per cent of observations in each tail of the distribution are removed from the sample (Long, 2000). Then, 95th percentiles, 5th percentiles and trimmed median of motorcycle acceleration are used as maximum, minimum and median values respectively. The threes values are inserted in VISSIM for one speed band. The six-step process above is conducted for all speed bands from 0 to 50 km/h. Figure shows upper bound, lower bound and median of desired acceleration of motorcycle in successive 5-km/h speed increments, which are 95th percentiles, 5th percentiles and trimmed median of motorcycle acceleration. Three curves in Figure B.1, which are used as 'desired acceleration functions' of motorcycle, are inserted in VISSIM.

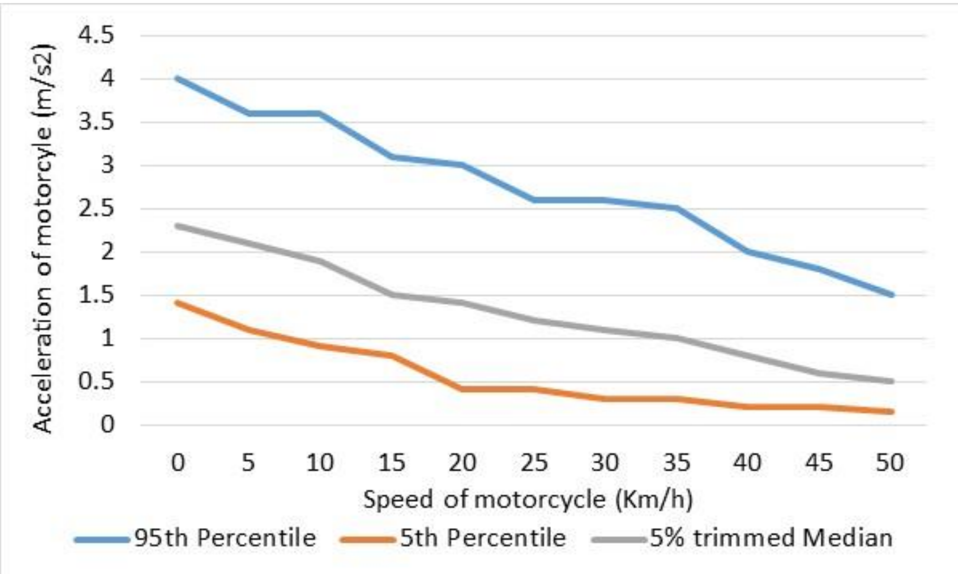

Figure B.1 Upper bound, lower bound and median of desired acceleration of motorcycle for the Hanoi case study

Figure B.2, which illustrates an example of the fourth step, shows the time-speed relationship of one observed motorcycle in the speed band between 2.5 km/h (0.7 m/s) and 7.5 km/h (2.1 m/s). The observed motorcycle accelerates from 0.7 to 2.1 m/s in the period from 0.32 to 1.16 seconds recorded in the speed gun. As can be seen from Figure B.2, the slope and correction coefficient are equal to 1.6479 and 0.9801 respectively.

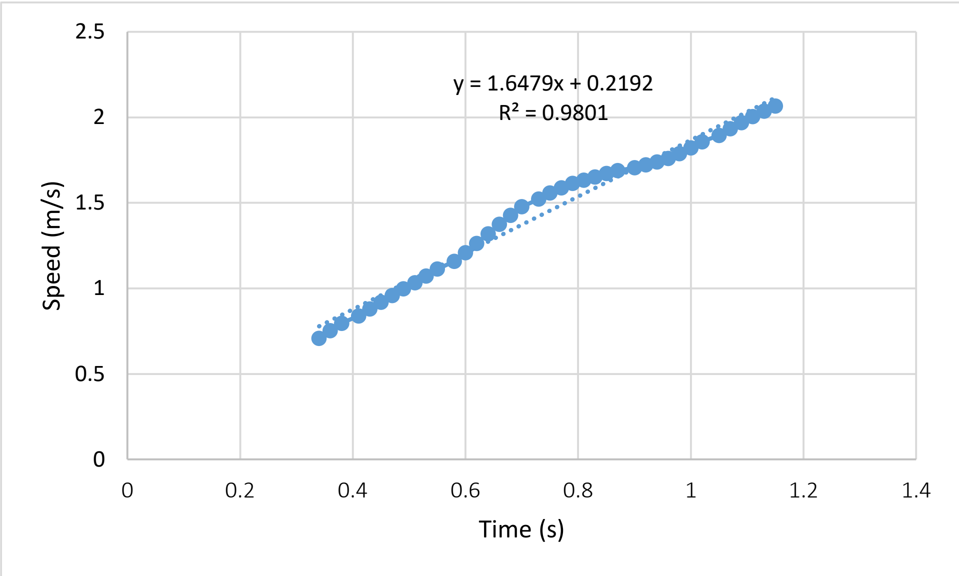

Figure B.2 Speed-time relationship of an observed motorcycle, speed of between 0.7-2.1 m/s

For the fifth step, 43 motorcycles were observed for the speed band of 2.5-7.5 km/h. The results show that 41 out of 43 sample correlation coefficient are higher than 0.90, 2 out of 43 sample correction coefficient are between 0.85 and 0.90. Therefore, for 5-km/h speed increments the speed-time linear model seems satisfactory. For the sixth step, the values of 95^{th} percentile, 5^{th} percentile and trimmed median are 3.66, 1.12 and 2.13 m/s^2 respectively.

Appendix C

This appendix shows an example calculation for the Metro option – Scenario 2 with the congestion charge scheme for the peak period. This example is for the first iteration after the introduction of elevated Metro.

Existing situation

The following parameters are obtained from the VISSIM simulation model and social cost model.

- Existing motorcycle travel time (tt_mc_0) = 5.59 minutes.

- Existing motorcycle fuel cost (cf_mc_0) = 760 VND/Km.

- Existing car travel time (tt_car_0) = 6.05 minutes.

- Existing car fuel cost (cf_car_0) = 2,376 VND/Km.

- Existing bus travel time (tt_bus_0) =6.80 minutes.

- Existing bus wait time (wt_bus_0) = 0.42 minutes.

- The utilities of motorcycle, car and bus are calculated as:

U_{mc_before} (U_{mc_0}) = *1.630348 - 0.01*4.8*tt_mc_0 - 0.0002116*cf_mc_0 = 1.201*

U_{car_before} (U_{car_0}) = *1.325391 - 0.0045*4.8*tt_car_0 - 0.0001628*cf_car_0 = 0.808*

U_{bus_before} (U_{bus_0}) = *0.665548 - 0.005149*4.8*tt_bus_0 - 0.0112216*wt_bus_0 = 0.4929*

Incremental elasticity analysis after an introduction of Metro

After the introduction of Metro, the following parameters are obtained from the VISSIM simulation model and social cost model.

- Motorcycle travel time (tt_mc_1) = 5.47 minutes.

- Motorcycle fuel cost (cf_mc_1) = 755.48 VND/km.

- Car travel time (tt_car_1) = 5.98 minutes.

- Car fuel cost (cf_car_1) = 2,360.88 VND/km.

- Remaining bus travel time (tt_bus_1) = 6.76 minutes.

- Remaining bus wait time (wt_bus_1) = 0.47 minutes.

- Metro travel time (tt_metro_1) = 3.40 minutes.

- Metro wait time (wt_metro_1) = 0.92 minutes.

Hence, the utilities of each mode in the after situation are estimated as:

U_{mc_after} (U_{mc_1}) = *1.630348 - 0.01*4.8*tt_mc_1 - 0.0002116*cf_mc_1 = 1.2081*

$U_{car\_ after}$ (U_{car_1}) = *1.325391 - 0.0045*4.8*tt_car_1 - 0.0001628*cf_car_1 = 0.8118*

$U_{bus\_ after}$ (U_{bus_1}) = *0.665548 - 0.005149*4.8*tt_bus_1 - 0.0112216*wt_bus_1 = 0.4931*

U_{Metro} (U_{metro_1}) = *0.996184 - 0.004496*4.8*tt_metro_1-0.0112216*wt_metro_1= 0.9125*

The utility of PT in the upper nest is:

$U_{pt} = 0.7532 \times ln\,(e^{Umetro} + e^{Ubus\_after}) = 1.067$

Change rate in a logsum is:

$$\frac{\Delta Logsum}{Logsum\_before} = \frac{Logsum\_after - Logsum\_before}{Logsum\_before}$$

$$Logsum\_before = Ln\left(e^{Ucar\_before} + e^{Umotorcycle\_before} + e^{Ubus\_before}\right) = 1.97459$$

$$Logsum\_after = Ln\left(e^{Ucar_{after}} + e^{Umotorcycle_{after}} + e^{U_{pt}}\right) = 2.14104$$

Change rate in total demand is therefore as:

$$\frac{\Delta Q}{Q} = \frac{Q_1 - Q_0}{Q_0} = \frac{\Delta Logsum}{Logsum\_before} = 0.0843$$

As existing demand (Q_0) is 19,000 pax in both directions, new total demand after the introduction of Metro (Q_1) is 19,000*(1+0.0843) = 20,601 pax.

Incremental nested logit model

Existing motorcycle, car and bus share are 77.38% (P_{mc_0}), 13.83% (P_{car_0}) and 8.79% (P_{PT_0} or P_{bus_0}) respectively.

Using equations in the study of Preston (1991), public transport's share in the upper nest is:

$$P_{PT\_1} = \frac{P_{PT\_0}\left[\exp\left(U_{metro\_1} - U_{bus\_0}\right) + \exp(U_{bus\_1} - U_{bus\_0})\right]^{\emptyset}}{P_{PT\_0}\left[\exp\left(U_{metro\_1} - U_{bus\_0}\right) + \exp(U_{bus\_1} - U_{bus\_0})\right]^{\emptyset} + \left[1 - P_{PT\_0}\right]}$$

where,

P_{PT_1} (P_{PT_0}) is the proportion choosing public transport in the after (before) the introduction of Metro;

$\emptyset$ is EMU parameter (or structural parameter for public transport nest). This value is 0.7532 for the Hanoi case study, based on the study of Hensher and Rose (2007) and modal share data in the study of the Japan International Cooperation Agency (2007).

$$P_{PT\_1} = \frac{8.79\%.\left[\exp(0.9125 - 0.4929) + \exp(0.4931 - 0.4929)\right]^{0.7532}}{8.79\%.\left[\exp(0.9125 - 0.4929) + \exp(0.4931 - 0.4929)\right]^{0.7532} + [1 - 8.79\%]}$$

So, $P_{PT\_1} = 16.21\%$

The lower nest are therefore:

$$P_{metro_1} = \frac{\exp(U_{metro_1} - U_{bus_0})}{\exp(U_{metro_1} - U_{bus_0}) + \exp(U_{bus_1} - U_{bus_0})}.P_{PT_1}$$

$$P_{metro_1} = \frac{\exp(0.9125 - 0.4929)}{\exp(0.9125 - 0.4929) + \exp(0.4931 - 0.4929)}.0.16206 = 9.78\%$$

and

$$P_{bus\_1} = \frac{\exp(U_{bus\_1} - U_{bus\_0})}{\exp(U_{metro\_1} - U_{bus\_0}) + \exp(U_{bus\_1} - U_{bus\_0})}.P_{PT\_1}$$

$$P_{bus_1} = \frac{\exp(0.4931 - 0.4929)}{\exp(0.9125 - 0.4929) + \exp(0.4931 - 0.4929)}.0.16206 = 6.43\%$$

The probabilities for motorcycle (P_{mc_1}) and car (P_{car_1}) in the upper nest are estimated as:

$$P_{mc\_1} = P_{mc\_0}\frac{1 - P_{PT\_1}}{1 - P_{PT\_0}} = 77.38\%\frac{1 - 16.206\%}{1 - 8.79\%} = 71.09\%$$

$$P_{car\_1} = P_{car\_0}\frac{1 - P_{PT\_1}}{1 - P_{PT\_0}} = 13.83\%\frac{1 - 16.206\%}{1 - 8.79\%} = 12.71\%$$

As new total demand after the introduction of Metro (Q_1) is 20,601 pax, new motorcycle, car, bus and Metro demands are 14,645; 2,618; 1,324 and 2,014 pax correspondingly.