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ASSESSING THE SOCIAL COSTS OF PUBLIC TRANSPORT IN A MIXED TRAFFIC ENVIRONMENT WITH ENDOGENOUS DEMAND

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Abstract

In reality, public transport (PT) passenger demand levels are influenced by internal factors rather than external ones, as they are shaped by the performance of public transport services such as price, service frequency and travel time. This paper develops a calculation process for PT endogenous demand with respect to social costs in motorcycle-dominated mixed transport systems, based on the total social cost of public transport in previous research. The incremental elasticity analysis is used to estimate the endogenous passenger demand for dedicated PT technologies. A case study of Quang Trung – Tran Phu – Nguyen Trai corridor in Hanoi is presented, highlighting the incremental elasticity analysis (IEA) of PT modes, including conventional buses, bus rapid transit (BRT), monorail and urban rail transit (URT), with a focus on passenger waiting and in-vehicle times. The findings reveal that conventional buses are most cost-effective for daily demands below 31,000 passengers per direction per day (pdd), while BRT is preferable for demands ranging from 31,000 to 55,000 pdd. The Monorail emerges as the most efficient option for demand between 55,000 and 165,000 pdd, with Urban Rail Transit (URT) becoming optimal when demand exceeds 165,000 pdd. These insights provide urban transport planners and policymakers with valuable guidance for strategic decision-making regarding new PT projects in mixed transport environments with a dominance of motorcycles.

Keywords: social cost; public transport; mixed traffic; endogenous demand.

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1. Introduction

Public transport (PT) is generally defined as transport services that provide for the general public [1]. PT plays an important role in daily commuting across countries worldwide. These services may include conventional bus, bus rapid transit (BRT), urban rail transit (URT) and Monorail, etc. Firstly, PT modes include conventional buses, which are the most widely used form of transit globally, with buses accounting for a significant share of passenger travel [2], such as around 40% in the U.S. in 2023 [3]. Bus Rapid Transit (BRT) offers a faster, rubber-tyred alternative with dedicated lanes, stations, and integrated systems [4]. Urban railway transit (URT) includes tram systems that operate at street level, light rail transit (LRT) that runs on exclusive rights-of-way, and underground metro systems that are fully segregated from other traffic [5]. Monorail systems come in two main types: suspension railways, such as the Wuppertal Monorail [6], and straddle-beam monorails, pioneered by ALWEG, used in places like Chongqing and Disneyland [7]. PT development has been focused on many cities in the world. Among the key factors considered when deciding to build a PT project are cost and demand. Of those, exogenous demand is often considered [8]. In addition, most research has focused on exogenous PT demand rather than endogenous PT demand [9]. Exogenous PT demand

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can be defined as demand influenced by external factors outside of PT the system such as income, car ownership, employment [10]. In addition, there are few studies on endogenous PT demand, both in general and specifically in mixed traffic environments. Internal factors within the PT system that shape endogenous demand include fare, in-vehicle time and service frequency. For example, the elasticity of bus and metro fares has been studied in Hanoi, Manila and Jakarta [11, 12]. However, the costs of PT systems were not considered in those studies. Moreover, it is essential to take into account endogenous demand, as internal factors become important criteria that can alter demand to reach a balanced state during operation. This reflects the practicality and adaptability of the public transport system. Therefore, this research emphasizes PT endogenous demand in relation to cost and time and considers several PT technologies within mixed transport system.

The social costs associated with PT include operator, user, and external costs [13]. The Fully Allocated Costs (FAC) model typically assumes that costs are a linear function of intermediate outputs like vehicle-hours, vehicle-distance, and peak vehicles to allocate operator costs [14]. Transit user costs include time spent accessing services, waiting, riding, transferring, and walking to final destinations [14, 15]. External costs are often calculated by multiplying the external unit costs of each PT mode by total vehicle kilometres, a method mainly applied in high-income countries [16]. For low- and middle-income countries, the benefit transfer method is used to estimate these costs based on data from developed countries [17].

The overall social costs of a mixed transport system consist of the combined social costs of both public and private transport, excluding infrastructure costs. Infrastructure costs for the mixed system include those specific to segregated public transport modes, such as Metro and Monorail, as well as the costs for shared lane infrastructure. The infrastructure costs of shared lanes are distributed among the transport modes using these facilities, such as cars, motorcycles, and conventional buses [18].

In terms of demand, there are three main approaches to modeling travelers' responses to cost. First, the fixed demand method is used when demand remains unaffected by cost, eliminating the need for a behavioral model. Second, the own-cost elasticity approach assumes that demand for travel between two locations is solely influenced by changes in the cost of a particular mode between those points. Lastly, the variable demand approach considers how the demand for each transport mode fluctuates based on the demand for other modes and associated cost factors. Discrete choice models are typically used to implement the full variable demand model [19].

For strategic-level PT investment, the elasticity of PT demand with respect to time/cost should be analysed. There has been studies on this analysis in the car-dominated environment which considered several PT modes such as single-decker bus, double-decker bus, modern light rail, underground [20, 21]. However, very few studies on this topic have been conducted for motorcycle-dominated environments. As a result, this study focuses on endogenous demand of PT with respect to social costs in a mixed transport with a dominance of motorcycles by using incremental elasticity analysis (IEA). Monorail, which has not been considered in this context, is also included in this research.

Time is one of the most important factors impacting on the service quality of PT. Moreover, the generalised journey time of PT passengers includes three main elements: walking time, waiting time and in-vehicle time. In general, the walking time is not changed with the level of demand. Hence, the attributes in the incremental elasticity analysis are chosen to be the passenger waiting time (WTT) and the in-vehicle time (IVT). The average value of elasticities for bus demand with respect to passenger waiting times can be −0.64, and values for off-peak journeys and journeys to non-central destinations seem to be higher [22]. There seems to be limited evidence on railway elasticities with respect to waiting time.

In-vehicle time elasticity for bus demand can be about −0.4 [23]. Similarly, those elasticities for urban buses seem to range from −0.4 to −0.6 while those for urban or regional rail range from −0.4 to −0.9 [24]. As a result, in the Demand Supply Model the demand elasticity with respect to in-vehicle time for bus users, light rail transit user and heavy rail transit users are −0.4, −0.6 and −0.8 respectively [20]. In-vehicle time elasticity is estimated as −0.37 for both peak and off-peak periods, while walk time elasticity are −0.1 for peak period and −0.24 for off-peak period [25].

The structure of this paper is as follows. Public transport social cost model and endogenous demand are developed in Section 2. Section 3 illustrates a case study of Hanoi. Section 4 presents the key results of the model. Section 5 discusses conclusions and potential future work.

2. Public transport social cost model and endogenous demand

This study applies a social cost model (SCM) for public transport, building on the single-mode social cost model for an urban mixed traffic corridor with a dominance of motorcycles discussed in previous studies [18, 20]. The original model focused on a single transport mode with fixed daily demand, ranging from 1,000 to 700,000 passengers per day per direction (pdd). The total social costs (*TSC*) comprise operator, user, and external costs, with external costs including elements such as accidents, noise, air pollution, and climate change costs. The operator costs cover both operational and capital expenditures, based on the Fully Allocated Costs model, while user costs include walking, waiting and in-vehicle time. The average social cost (ASC) of each PT mode is estimated as:

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

where *PKM* is total passenger-kilometres, which is calculated by multiplying the total passenger demand for each transport mode by the average length of a passenger's journey.

The endogenous demand calculation in the study by Li and Preston [20] is revised in this study. Based on the changes in level of service (waiting time and in-vehicle time), the endogenous PT demand is estimated as:

$$Q_1 = Q_0 * \left(\frac{T^1_{wait}}{T^0_{wait}}\right)^{E_1} * \left(\frac{T^1_{IVT}}{T^0_{IVT}}\right)^{E_2} \tag{2}$$

where Q_1 is endogenous demand due to the changes of passenger waiting time and passenger in-vehicle time for each period, including peak-hour, off-peak (passenger); This is different to the study by Li and Preston [20] that endogenous demand is estimated for the whole day; Q_0 is input existing demand for each period, which is calculated form existing daily demand (passenger); T^1_{wait} is passenger waiting time at current demand level of the PT mode; T^0_{wait} is base passenger waiting time (hours); T^1_{IVT} is passenger in-vehicle time at current demand level of the PT mode; T^0_{IVT} is base passenger in-vehicle time (hours); E_1 is demand elasticity with respect to PT passenger waiting time. The waiting time elasticity of −0.64 and −0.4 can be used for sensitivity analysis; E_2 is demand elasticity with respect to PT passenger in-vehicle time. The demand elasticity with respect to in-vehicle time for bus users, monorail user and urban railway transit users are −0.4, −0.6 and −0.8 respectively.

The incremental elasticity analysis is used to estimate the endogenous passenger demand for dedicated public transport technologies. Fig. 1 shows the endogenous demand calculation iteration.

The daily passenger demands are split into four periods including pear hour (2 hours), peak period (3 hours), mid-day off-peak (7 hours) and morning-evening off-peak (3hours). Therefore, the revised flow chart in Fig. 1 is run separately for each of these four periods. The final step involves summing the endogenous demand from each of the four time periods to calculate the daily passenger endogenous demand for each exogenous demand. Two scenarios can occur in the calculation of endogenous demand.

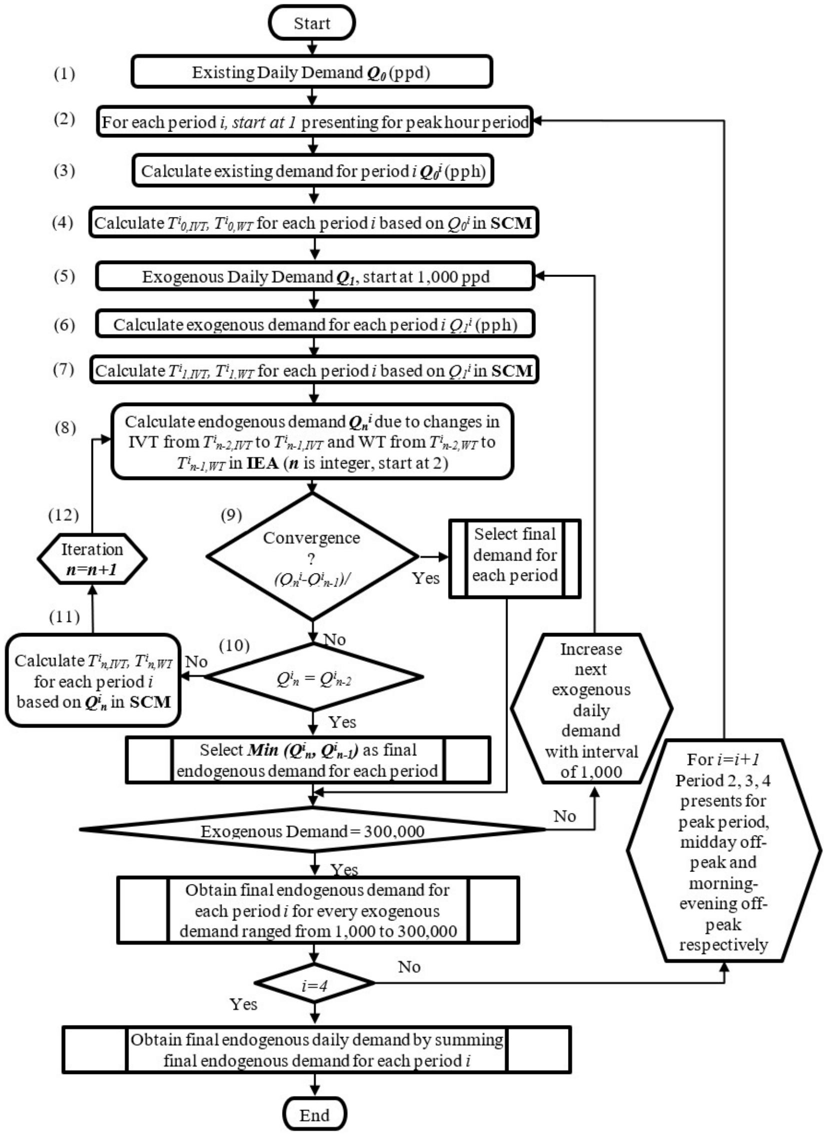


Figure 1. Revised flow chart for the endogenous demand calculation iteration

The definition of 'Convergence' term

The convergence is achieved when the difference between the previous demand and the new endogenous demand is less than 1%.

$$\frac{Q_n^i - Q_{n-1}^i}{Q_{n-1}^i} < 1\% \tag{3}$$

where n is integer ($n \geq 2$); Q_{n-1}^i is previous endogenous demand for each period i (passenger per hours - *pph*); Q_n^i is new endogenous demand for each period i (*pph*);

The definition of '$Q_n^i = Q_{n-2}^i$' term

When the convergence is not forever achieved, the following situation occurs:

$$\left(\frac{T_{n-1,WT}^i}{T_{n-2,WT}^i}\right)^{E_1} * \left(\frac{T_{n-1,IVT}^i}{T_{n-2,IVT}^i}\right)^{E_2} = 1 \tag{4}$$

As a result,

$$Q_n^i = Q_{n-2}^i * \left(\frac{T_{n-1,WT}^i}{T_{n-2,WT}^i}\right)^{E_1} * \left(\frac{T_{n-1,IVT}^i}{T_{n-2,IVT}^i}\right)^{E_2} = Q_{n-2}^i \tag{5}$$

where $T_{n-1,WT}^i$ is passenger waiting time for period i, which is calculated based on Q_{n-1}^i in the SCM; $T_{n-2,WT}^i$ is passenger waiting time for period i, which is calculated based on Q_{n-2}^i in the SCM; $T_{n-1,IVT}^i$ is passenger in vehicle time for period i, which is calculated based on Q_{n-1}^i in the SCM; $T_{n-2,IVT}^i$ is passenger in vehicle time for period i, which is calculated based on Q_{n-2}^i in the SCM;

When '$Q_n^i = Q_{n-2}^i$' term occurs, new demand for each period i at iteration $n+1$ is estimated as:

$$Q_{n+1}^i = Q_{n-1}^i * \left(\frac{T_{n,WT}^i}{T_{n-1,WT}^i}\right)^{E_1} * \left(\frac{T_{n,IVT}^i}{T_{n-1,IVT}^i}\right)^{E_2} \tag{6}$$

however, $Q_n^i = Q_{n-2}^i$ causes $T_{n,WT}^i = T_{n-2,WT}^i$ and $T_{n,IVT}^i = T_{n-2,IVT}^i$ then

$$Q_{n+1}^i = Q_{n-1}^i * \left(\frac{T_{n-2,WT}^i}{T_{n-1,WT}^i}\right)^{E_1} * \left(\frac{T_{n-2,IVT}^i}{T_{n-1,IVT}^i}\right)^{E_2} = Q_{n-1}^i \tag{7}$$

The reason for '$Q_n^i = Q_{n-2}^i$' term is that change in IVT and change in WT are inversely proportional to each other.

In situations where demand (flow) exceeds capacity, an increase in demand causes a decrease in speed, therefore, in-vehicle time rises. On contrary, a rise in demand results to a reduction in waiting time. Hence, there is a possibility for occurring $Q_n^i = Q_{n-2}^i$' term. From a mathematical perspective, there is always one solution for the following equation under the conditions below:

$$\left(\frac{T_{n-1,WT}^i}{T_{n-2,WT}^i}\right)^{E_1} * \left(\frac{T_{n-1,IVT}^i}{T_{n-2,IVT}^i}\right)^{E_2} = 1 \tag{8}$$

- If $E_1, E_2 < 0$; and

$$\left(\frac{T_{n-1,WT}^i}{T_{n-2,WT}^i}\right) < 1, \quad \left(\frac{T_{n-1,IVT}^i}{T_{n-2,IVT}^i}\right) > 1 \quad \text{or} \quad \left(\frac{T_{n-1,WT}^i}{T_{n-2,WT}^i}\right) > 1, \quad \left(\frac{T_{n-1,IVT}^i}{T_{n-2,IVT}^i}\right) < 1 \tag{9}$$

It is essential to choose Q_n^i or Q_{n-1}^i as final endogenous demand for each period i. The endogenous demand value, which is close to existing demand should be chosen.

3. Case study

Similar to the previous studies [18, 26, 27], the Nguyen Trai - Tran Phu - Quang Trung corridor, which is 7.0 km length, in Hanoi, Vietnam is selected as a case study. The URT line 2A has been operated on this major arterial, which has four lanes per direction. All basic input parameters from the PT social cost model for this corridor in the study by Vu and Preston [26] are used for estimating PT endogenous demand in this research. Conventional bus, BRT, Monorail and URT are considered in this study. In other words, the calculation of PT endogenous demand with respect to waiting and in-vehicle time is conducted step by step, as illustrated in Fig. 1. For each PT mode, different values of existing demand are implemented in the calculation process to estimate endogenous demand.

4. Results

4.1. Relationship between the endogenous demand and exogenous demand

Figs. 2–5 were produced to show the relationship between the endogenous demand and exogenous demand for PT technologies with different existing demand levels.

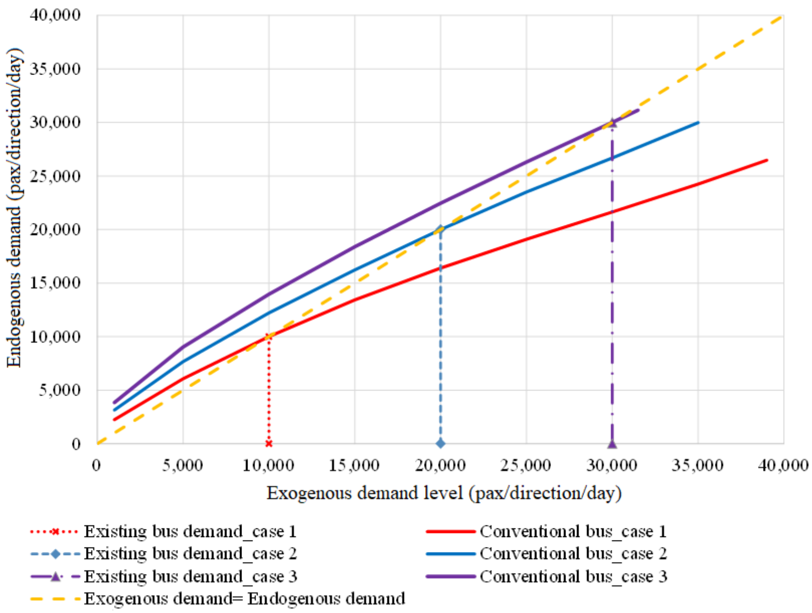


Figure 2. Exogenous demand and endogenous demand relationship for conventional bus

As can be seen from Figs. 2–5, some findings can be summarized as follows:

- For each PT technology with a given existing demand level, there is always one maximum value of the exogenous demand, which is higher than demand at PT vehicle capacity in 'peak hour' period. Indeed, the demands at capacity in 'peak hour' period for four these PT modes are 31,000; 56,000; 169,000 and 430,000 pdd respectively in the SCM. There seem to be two reasons for the maximum exogenous demand. Firstly, due to the limited infrastructure capacity, PT demand can not increase infinitely. Secondly, the existing demand level is assumed smaller than the demand level at PT vehicle capacity. Hence, any initial increase from the existing demand level to a threshold in congested situation can lead to a deterioration service, which can bring the level of demand back to the maximum level.

- When the exogenous demand is less than existing demand, the final endogenous demand is higher than the exogenous demand but smaller than the existing demand. Conversely, when the exogenous demand exceeds existing demand, the final endogenous demand is smaller than the exogenous demand but greater than the existing demand. In other words, any transport policy or planning strategy that initiates a change in existing demand, then, due to 'Supply is equal to Demand' rule, the final endogenous demand might experience a change, which is smaller than the initial change.

- For a given existing demand level, the relationship between exogenous demand and endogenous demand is identified by using the IEA and the SCM. At higher existing bus demand levels, the maximum endogenous demand is greater because the higher existing demand is closer to the demand level at infrastructure capacity, resulting in a smaller change in demand. Starting from a lower existing demand level in the demand calculation iteration, the final endogenous demand corresponding to this existing demand is determined. Consequently, when a higher existing demand, which is close to the final endogenous demand from the previous calculation iteration, is run in the IEA, a new endogenous demand level is therefore identified. For example, with an existing bus demand of 10,000 pdd, the maximum endogenous demand is about 27,000 pdd. Then, for an existing demand of 30,000 pdd, which is close to 27,000 pdd, the maximum endogenous is around 31,000 pdd, which can be the highest value of demand for the conventional bus (see Fig. 2). This indicates that when the demand exceeds 31,000 pdd, a higher person capacity of the bus vehicle or a new public transport technology might be required to meet this demand. Double decker bus or BRT might be the potential solutions.

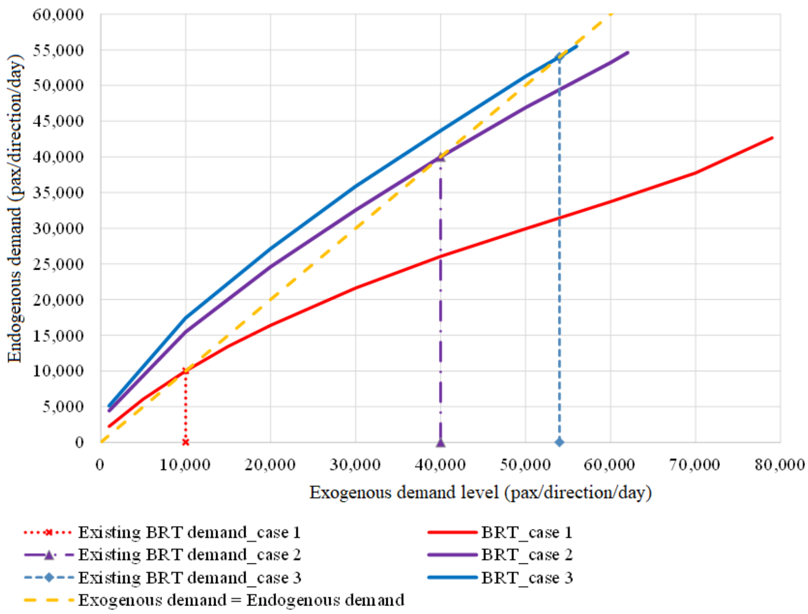


Figure 3. Exogenous demand and endogenous demand relationship for the BRT

- Fig. 3 indicates that the maximum endogenous BRT demand is approximately 55,000 pdd. When the demand is higher than 55,000 pdd, a higher person capacity BRT vehicle or a new PT mode is required to supply this demand, for example Monorail.

As shown in Fig. 4, the maximum endogenous Monorail demand is about 165,000 pdd. This means that when demand exceeds 165,000 pdd, a new PT technology (such as URT) or Monorail with additional car units might be required to meet this demand.

Fig. 5 compares the relationship between endogenous URT demand and the exogenous URT demand as the passenger wait time elasticity changes. For this sensitivity test, when the exogenous demand is lower than the existing demand, a lower wait time elasticity (i.e. −0.4 compared to −0.64)

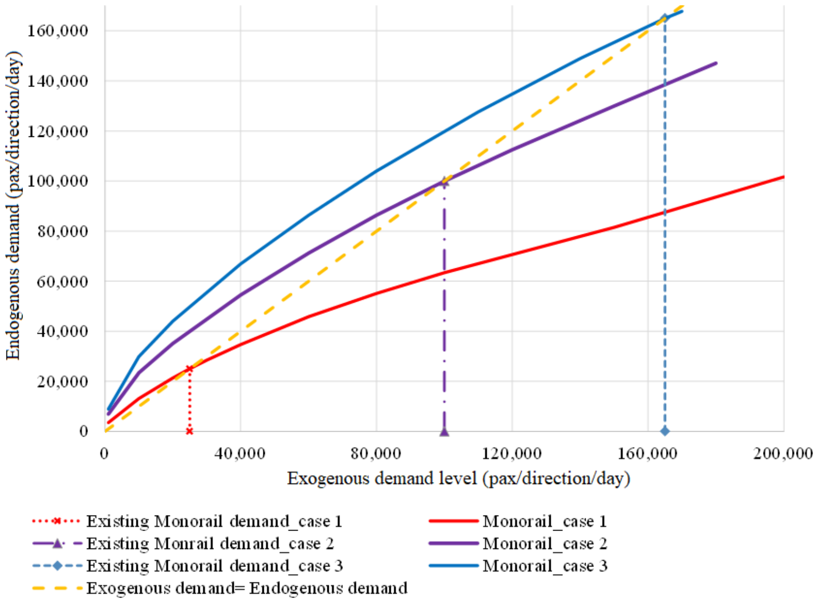


Figure 4. Exogenous demand and endogenous demand relationship for the Monorail

can cause a higher final endogenous demand. On the contrary, when the exogenous demand is higher than the existing demand, a lower wait time elasticity might result in a lower final endogenous demand. In conclusion, a lower wait time elasticity can lead to a smaller change in demand given the same existing demand.

The maximum endogenous URT demand appears to be around 420,000 pdd (see Fig. 5). This indicates that when demand exceeds this number, an increase in the number of URT car unit might be required to accommodate the demand.

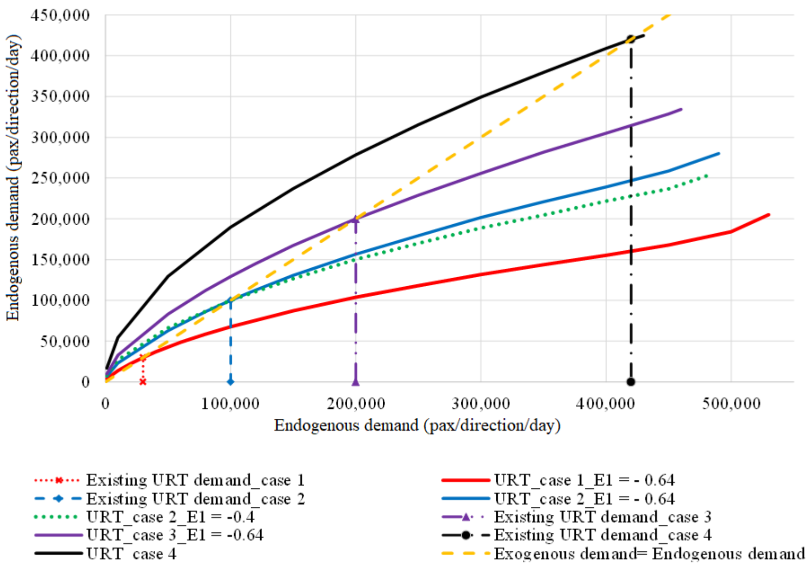
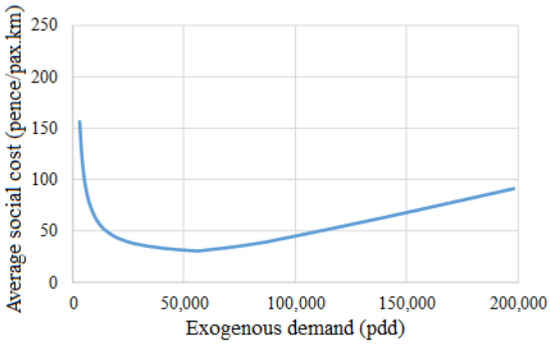


Figure 5. Exogenous demand and endogenous demand relationship for the URT

4.2. Endogenous demand effects on average social cost

The analysis of the demand and supply relationship demonstrates how the actual PT performance can affect the passenger demand level through IEA. The actual passenger demand can then be substituted back to the SCM to estimate the average social costs by using the endogenous demand. To establish the effects of applying endogenous demand to the SCM, an illustration is show below. The average social cost (ASC) of dedicated BRT is calculated by using both the SCM and IEA, and the results are shown in Fig. 6.



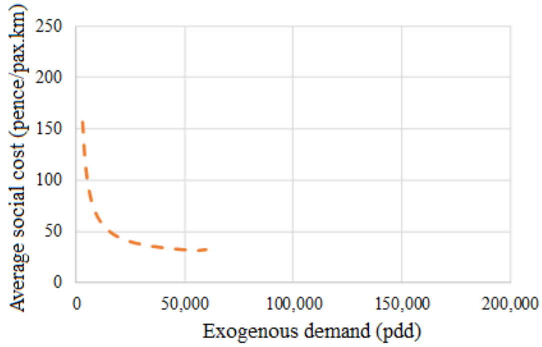


Figure 6. ASC of dedicated BRT in exogenous and endogenous demand

In Fig. 6, the average social cost of dedicated BRT after applying the endogenous demand analysis is shown as the dotted line on the right hand side, and the blue solid line indicates the average social cost of dedicated BRT before applying the endogenous demand calculation. The endogenous demand curve stops at the daily demand level of around 55,000 pdd, which means the level of demand cannot exceed 55,000 pdd. When the maximum point has been reached, any increase in demand will cause a deterioration service which will bring the demand back to maximum level.

The minimum social cost graphs are produced for both exogenous demands and after applying the endogenous demand analysis. Figs. 7 and 8 show minimum ASC of exclusive PT modes before and after applying endogenous demand respectively.

Fig. 8 illustrates that the conventional bus has the lowest ASC when the daily demand is less than 31,000 pdd due to its low vehicle and infrastructure costs despite having lower vehicle capacity. With higher vehicle capacity than the conventional bus, BRT shows great potential when demand ranges from 31,000 to 55,000 pdd. The Monorail achieves the lowest ASC within the demand level range of 55,000 to 165,000 pdd. The URT has the highest default value capacity among four PT technologies. For demand above 165,000 pdd, URT shows the lowest ASC, while the costs for the conventional bus and BRT become extremely high as the number of vehicles required exceeds infrastructure capacity, leading to increased congestion and higher user costs. Additionally, the Monorail reaches its maximum endogenous demand at this level.

In addition, Fig. 8 shows the discontinuities between the ASC curves because of some following reasons. Firstly, after reaching the maximum endogenous demand of approximately 31,000 pdd, the conventional bus becomes less attractive to passengers due to significantly longer in-vehicle time and comparable waiting time compared to BRT. Furthermore, an increase in bus demand, which leads to much higher passenger in-vehicle times, causes existing bus users to shift to other modes such as motorcycles or cars. As a result, the actual demand level decreases, and the average cost curve for the conventional bus terminates at that point to reflect the impact of endogenous demand. Secondly, at maximum endogenous bus demand, ASC of BRT is greater than that number of the conventional bus. The gap of the discontinuity can be reduced if the ASC of BRT decreases. One solution might

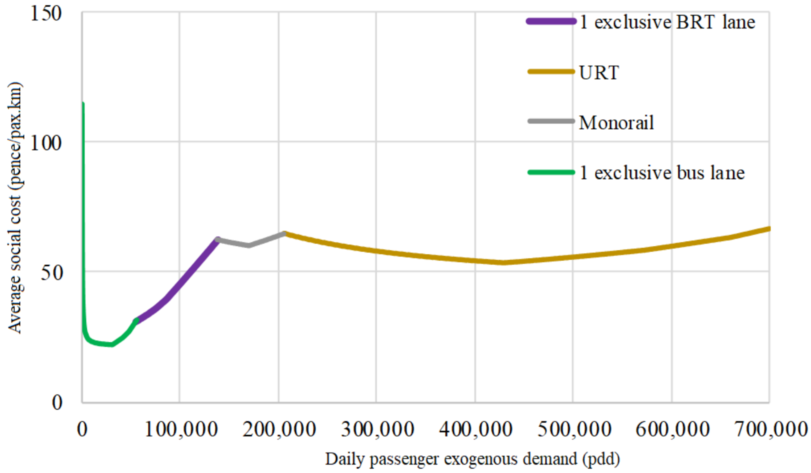


Figure 7. Minimum average social cost of exclusive PT modes

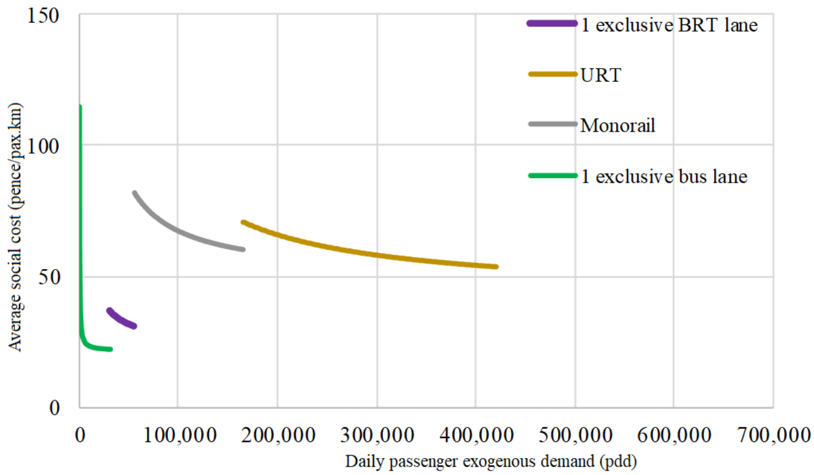


Figure 8. Minimum ASC of exclusive PT modes after applying endogenous demand

be to increase the person capacity of BRT vehicle or improve capacity utilization. This situation also occurs between BRT and Monorail, as well as between Monorail and URT when their attractiveness is lower than that of next mode. Solutions for reducing the gap of discontinuities between BRT and Monorail, or between Monorail and URT, could include rising car units for Monorail and URT.

Hanoi has adjusted the planning of the urban railway network and improved the bus network. In these adjustments to the planning and improvement projects, transport planners and decision-makers should forecast the total traffic demand along the PT corridor, as well as the modal share of private transport (cars and motorcycles) and PT. The endogenous PT demand should be then considered to reassess whether the planned PT mode is suitable and whether adjustments to the PT mode align with the endogenous demand and costs.

5. Conclusions

This study presents an elasticity analysis of PT endogenous demand in relation to cost and time, building upon the social cost model for PT used in previous research. The calculation process for PT endogenous demand has been refined from the approach in the study by [20]. Additionally, the Monorail, which had not been previously considered in this context, is included in the analysis. Urban transport planners and policymakers in cities with motorcycle-dominated mixed traffic can gain valuable insights from this case study. When the exogenous demand of a PT corridor is forecasted during the planning process, the endogenous demand might be estimated based on the results of this study. Therefore, the expected PT mode should be reevaluated and changed according to the estimated endogenous demand and total costs.

For a range of demand, one PT mode has advantage by estimating endogenous demand rather than exogenous demand because passengers' responses to costs are considered. This finding is also supported by the study in [8]. However, the values of demand range are different between this study and [8]. Indeed, the conventional bus is most cost-effective for daily demand below 31,000 passengers due to its low vehicle and infrastructure costs but limited capacity. BRT becomes more advantageous when demand ranges from 31,000 to 55,000 passengers, offering higher capacity. For demand between 55,000 and 165,000 passengers, the Monorail demonstrates the lowest average social cost (ASC). When demand exceeds 165,000 passengers, the URT becomes the most efficient option, as the conventional bus and BRT face capacity constraints and increased congestion, and the Monorail reaches its demand limits.

Each public transportation mode has a maximum demand point, beyond which this mode might become inefficient. At that point, a new PT mode is considered. The approach of estimating PT endogenous demand and findings in this study can be used for selecting alternatives at a strategic level for the next detailed assessment for deciding whether to develop a new urban PT project.

However, some limitations and future research directions of this study include:

All fundamental input parameters from the PT social cost model for this corridor, as outlined in the study by Vu and Preston [26], are employed in this research to estimate the endogenous PT demand. This data should be updated.

Further research is needed on transportation demand forecasting across the entire network at the planning stage to predict demand for each corridor.

It is necessary to combine this with the detailed evaluation step to develop a complete framework for selecting new public transportation modes in an investment project.

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Appendix

Calculation examples of endogenous demand and exogenous demand relationship for conventional bus by using VBA Excel.

Case 1: 'Convergence' term is achieved

- Step 1 in Fig. 1: For chosen corridor in Hanoi, the existing bus passenger demand Q_0 is 37,000 ppd.

- Step 2: Value of i starts at 1, presenting for peak hour.

- Step 3: Bus passenger demand in peak hour Q_0^1 is 3,700 pax/hour.

- Step 4: In the cost model, $T_{0,IVT}^1$ is calculated as 0.174 hours, $T_{0,WT}^1$ is calculated as 0.00555 hours.

- Step 5: Start with Daily Exogenous demand of 1,000 ppd.

- Step 6: Bus passenger demand in peak hour Q_1^1 is 100 pax/hour.

- Step 7: In the cost model, $T_{1,IVT}^1$ is calculated as 0.1204 hours, $T_{1,WT}^1$ is calculated as 0.1824 hours.

- Step 8: Due to changes in IVT from $T^1_{0,WT}$ to $T^1_{1,WT}$ and in WTT from $T^1_{0,IVT}$ to $T^1_{0,IVT}$, new endogenous demand Q^1_2 is calculated based on Q^1_0 by the following equation:

$$Q^1_2 = Q^1_0 * \left(\frac{T^1_{1,WT}}{T^1_{0,WT}}\right)^{-0.64} * \left(\frac{T^1_{1,IVT}}{T^1_{0,IVT}}\right)^{-0.4}$$

As a result, Q^1_2 = 458.6 pax/hour.

- Step 9: Check convergence?

$$\frac{Q^1_2 - Q^1_1}{Q^1_1} = 359\% > 1\%$$

Convergence is not achieved, therefore, step 10 is implemented.

- Step 10: Check '$Q^i_n = Q^i_{n-2}$' term?

$$Q^1_2 = 458.6 \neq Q^1_0 = 3{,}700$$

This term is not achieved, hence, step 11 and step 12 are implemented.

- Step 11: In the cost model, $T^1_{2,IVT}$ is calculated as 0.1204 hours, $T^1_{2,WT}$ is calculated as 0.04028 hours.

- Step 12: $n = 2 + 1 = 3$, this means that Q^1_3 need to be calculated due to changes in IVT from $T^1_{1,WT}$ to $T^1_{2,WT}$ and in WTT from $T^1_{1,IVT}$ to $T^1_{2,IVT}$. Generally, iterations from step 8 to step 12 are implemented until one condition in step 9 or step 10 in Fig. 1 is achieved. For this example, Q^1_3 is calculated in IEA as:

$$Q^1_3 = Q^1_1 * \left(\frac{T^1_{2,WT}}{T^1_{1,WT}}\right)^{-0.64} * \left(\frac{T^1_{2,IVT}}{T^1_{1,IVT}}\right)^{-0.4}$$

As a result, Q^1_3 is equal to 263 pax/hour.

Iterations from step 8 to step 12 until Q_8 of 305.7 (pax/hour). The reason for that Q_7 is equal to 305 and therefore convergence is achieved (see Appendix in more details). The final endogenous for peak hour period is 305.7 (pax/hour).

Carry out the same calculation iteration above for peak period ($i = 2$), mid-day off-peak ($i = 3$) and morning_evening off-peak ($i = 4$), the final endogenous are 270, 268 and 265 correspondingly. Therefore, the final endogenous daily demand is 2,761 ppd with respect to the exogenous demand of 1,000 ppd.

Case 2: '$Q^i_n = Q^i_{n-2}$' term is achieved

- Step 1 in Fig. 1: For chosen corridor in Hanoi, the existing bus passenger demand Q_0 is 37,000 ppd.

- Step 2: Value of i starts at 1, presenting for peak hour.

- Step 3: Bus passenger demand in peak hour Q^1_0 is 3,700 pax/hour.

- Step 4: In the cost model, $T^1_{0,IVT}$ is calculated as 0.174 hours, $T^1_{0,WT}$ is calculated as 0.00555 hours.

- Step 5: Start with Daily Exogenous demand of 26,000 ppd.

- Step 6: Bus passenger demand in peak hour Q^1_1 is 2,600 pax/hour.

- Step 7: In the cost model, $T^1_{1,IVT}$ is calculated as 0.12 hours, $T^1_{1,WT}$ is calculated as 0.008 hours.

- Step 8: Due to changes in IVT from $T^1_{0,WT}$ to $T^1_{1,WT}$ and in WTT from $T^1_{0,IVT}$ to $T^1_{0,IVT}$, new endogenous demand Q^1_2 is calculated based on Q^1_0 by the following equation:

$$Q^1_2 = Q^1_0 * \left(\frac{T^1_{1,WT}}{T^1_{0,WT}}\right)^{-0.64} * \left(\frac{T^1_{1,IVT}}{T^1_{0,IVT}}\right)^{-0.4}$$

As a result, Q^1_2 = 3,497 pax/hour.

- Step 9: Check convergence?

$$\frac{Q^1_2 - Q^1_1}{Q^1_1} = 35\% > 1\%$$

Convergence is not achieved, therefore, step 10 is implemented.

- Step 10: Check '$Q^i_n = Q^i_{n-2}$' term?

$$Q^1_2 = 3,497 \neq Q^1_0 = 3,700$$

This term is not achieved, hence, step 11 and step 12 are implemented.

- Step 11: In the cost model, $T^1_{2,IVT}$ is calculated as 0.155 hours, $T^1_{2,WT}$ is calculated as 0.006 hours.

- Step 12: $n = 2 + 1 = 3$, this means that Q^1_3 need to be calculated due to changes in IVT from $T^1_{1,WT}$ to $T^1_{2,WT}$ and in WTT from $T^1_{1,IVT}$ to $T^1_{2,IVT}$. Generally, iterations from step 8 to step 12 are implemented until one condition in step 9 or step 10 in Fig. 1 is achieved. For this example, Q^1_3 is calculated in IEA as:

$$Q^1_3 = Q^1_1 * \left(\frac{T^1_{2,WT}}{T^1_{1,WT}}\right)^{-0.64} * \left(\frac{T^1_{2,IVT}}{T^1_{1,IVT}}\right)^{-0.4}$$

As a result, Q^1_3 is equal to 2,787 pax/hour.

Iterations from step 8 to step 12 stops at Q_{35} of 3,020 (pax/hour). The reason for that Q_{33} is equal to 3,020 and therefore '$Q^i_n = Q^i_{n-2}$' term is achieved (see Appendix in more details). Q_{34} is equal to 3,285. If one more iteration is implemented, Q_{36} is equal to 3,285. Hence, the smaller demand of 3,020 is chosen as final endogenous for peak hour period.

Carry out the same calculation iteration above for peak period ($i = 2$), mid-day off-peak ($i = 3$) and morning_evening off-peak ($i = 4$), the final endogenous are 2,873; 2,870 and 2,863 correspondingly. However, for these calculation iteration, only 'convergence' is achieved and '$Q^i_n = Q^i_{n-2}$' term is not occurred. Therefore, the final endogenous daily demand is 29,003 ppd with respect to the exogenous demand of 26,000 ppd.

By evaluating the 300 demand levels from 1,000 to 300,000 passengers per day for URT, BRT, Monorail and Conventional bus with the process in Fig. 1, the following Figures were produced to show the relationship between the endogenous demand and the exogenous demand for public transport technologies in different periods.