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Valuation of Travel Time Savings in Commuting Traffic by Introducing a New Monorail System to Colombo City

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Abstract

This study estimates the value of travel time savings (VTTS) for commuters who travel to Colombo city in traffic congestion when the proposed monorail system is in place. The model considers a mono-centric city with symmetrically distributed radial highways converging toward the central business district (CBD),with an inelastic commuter demand. The model assumes that the congestible highway and the congestion-free monorail can be accessed at all points along the travel corridor, but travelers only exit at the CBD. We compare the aggregate travel time savings (ATTS) from different monorail scenarios, with the introduction of a toll as a necessary condition to generate an efficient outcome. The results show that for a monorail running at an average speed of 40 km/h a length of 26.3 km from the CBD will optimize investment and contribute travel time savings of 105 million Rs. per day or 189 million USD per year to the Sri Lankan economy. A sensitivity analysis is conducted to evaluate the effects of monorail speed, commuter income, social interest rate, employment density distribution, and population growth on ATTS.

Keywords: VTTS, Traffic Congestion, Monorail, Commuters, Mono-Centric City

1 Introduction

Commuting takes up a large portion of an individual's time, and traffic congestion increases it significantly. It became an acute problem in many cities in developing countries such as Colombo, the commercial capital of Sri Lanka. As a result of urban development and economic growth, the Colombo Metropolitan Area (CMA) has dramatically increased in size during the last few decades. This rapid urban expansion has led to suburbanization, a longer average journey length for commuters, and increased use of private vehicles. This resulted in severe traffic congestion with speeds as low as 8 km/h during the peak congestion period at the boundary of Colombo city. At present, 70% of commuting trips to CMA start 20 to 40 km away from the city center and enter the city through seven key corridors. It is estimated that current travel demand will increase by 75% by 2035. The share of the higher income group is estimated to increase from 7.6% in 2012 to 56.3% in 2035, it is expected that the number of passengers using private modes of transportation will increase by approximately 2.5 times while the number of passengers using public transport will remain at a roughly static value (CoMTrans Urban Transport Master Plan Executive Summary: Final Report 2014). As a result, current commuters are conscious about saving travel time.

In response, the government has prioritized a number of transport infrastructure and service improvement projects that are developed in line with the National Transport Policy, Ministry of Transport (2009) and "The Emerging Wonder of Asia", the 10-year Development Framework (2010-2020). Accordingly, policies to promote public transport and alleviate urban traffic congestion were emphasized in the CoMTrans Urban Transport Master Plan (2014). In translating the policies into reality, the Feasibility Study of Skytrain Project (2014) evaluates travel time savings, vehicle operating costs, accident costs and construction costs and suggests the construction of monorail over a total length of 17.1 km to connect the Central Business District (CBD) to the suburban areas.

The majority of transport investments bring benefits to transport users in terms of the value of travel time savings (VTTS), which is the key parameter in benefit-cost analysis and travel demand modelling (Small, 2012), and the proposed monorail system in Sri Lanka is expected to do the same. Theoretical arguments and empirical evidence on passenger transport confirm that people place value on travel time savings. Mackie, Jara-Diaz, and Fowkes (2001) found that VTTS accounts for approximately 80% of the monetized benefits in major road schemes in the UK.

The study aims to identify an optimal urban transportation system in Colombo, including the speed and the length of the monorail. Further, the study identifies alternative policies such as the provision of a park-and-ride facility to complement the monorail project. To address this issue, we use the standard urban spatial models as in Anas and Moses (1979) and Yoshida (2011) to estimate the traffic volume in the CBD followed by a comprehensive analysis to determine the best policy to implement. The study finds, inter alia that, for a monorail running at an average speed of 40 km/h a length of 14.0 km from the CBD will optimize investment and contribute travel time savings of 179 million USD per year to the Sri Lankan economy.

The remainder of this paper is organized as follows. Section 2 presents the theoretical framework of the analysis. Section 3 discusses the results of simulation analysis for different scenarios and compares them with the benchmark without the monorail. We consider different parameters for the monorail speed, income, social interest rate, population density gradient, and population growth. Finally, Section 4 concludes.

2 Theoretical Framework

The model stipulates a circular city with radial highways connecting the suburbs with the CBD.[1] Highway extends indefinitely while the monorail along it has finite length. We assume circular symmetry as for the geography of the city including the orientation of highways and monorails, and hence limit our analyis to a single market area along a highway which is an arc. To simplify the model, it is assumed that the capacity of the highway and the speed of the monorail are constant throughout the corridor, i.e., the highway is capacity-constrained and congestible while the monorail is not.

We consider a morning rush hour where people who travel along the highway to the CBD are all commuters, and therefore their travel demand is inelastic to trip price. Trip price is consisted of user's time cost and if any, monetary cost e.g. toll.

The commuter can access the highway or the monorail at any point along the corridor, but the exit will be only at the CBD. The commuters reach the highway or the monorail from their residences traveling circumferentially. We assume for simplicity the circumferential access travel is costless. Commuters are homogeneous and thus have the same value of time, and choose the mode with a lower price.[2]

Let us denote by θ the angle of the market area in radian and by x the distance from CBD. Then the market area at distance x is $\theta x dx$. Let $E(x)$ be the employment density.[3] Then we have

[1] Size of CBD is assumed to be negligible.

[2] We assume that mode-switching cost is negligibly positive. As a result, there are three types of commuters: those who drive all the way, those who take the monorail, and those who drive to the monorail terminal and take the monorail into CBD.

[3] Population densities are converted to employment densities, as explained below, by using workforce participation rate and employment rate data of the country.

the commuting volume at x, say $Q(x)$, to be such that

$$Q(x) = \int_x^\infty E(\tilde{x})\,\theta\tilde{x}\,d\tilde{x}$$

where $Q'(x)$ is hence the commuting demand at location x.

Let $Q_A(x)$ be the commuting volume of automobiles and $Q_M(x)$ be the commuting volume on the monorail at location x, so that we have $Q = Q_A + Q_M$ for any x.

Costs Total costs are consisted of three parts; aggregate travel time cost of users, monorail system costs, and the park-and-ride facility cost.[4] Let us define $c(x)$ as the user cost of traveling distance of dx at location x on the highway. Given that the highway capacity is constant, $c(x)$ is increasing in $Q_A(x)$. Following literature we specify $c(x)$ as suggested by the Bureau of Public Roads (BPR):

$$c = \omega_0 + \omega_1 Q_A^\gamma + \tau$$

for any x where ω_0, ω_1, and γ are positive parameters and τ is toll per unit distance.[5] We set the toll at the marginal external cost (MEC) of congestion, and it is lifted where monorail is not available. The monorail speed is assumed to be constant, and so is the travel time per unit distance at any x; the user cost of the monorail is a constant, say m per unit distance.[6] Let us denote by $\bar{x}$ the location of monorail terminal, or equivalently, the length of monorail. Equilibrium implies that

$$c = \begin{cases} m & x \leq \bar{x} \\ \omega_0 + \omega_1 Q^\gamma, & x > \bar{x}. \end{cases}$$

Note that $c = m$ implies that Q_A and τ are constant for $x \leq \bar{x}$.[7] Aggregate travel time cost of users C is then

$$C = \int_0^{\bar{x}} \left[mQ(x) - \tau Q_A\right] dx + \int_{\bar{x}}^\infty c(x)\,Q(x)\,dx.$$

Monorail's cost is the sum of capital cost and the operating cost and is denoted by $M(\bar{x})$. This implies that the monorail's cost is insensitive to the passenger volume. Park-and-ride facility cost $F(K)$ is increasing in its capacity K; the capacity must be large enough to accomodate all those who switch to monorail at the terminal station so that we have $K \geq Q_M(\bar{x})$ with the equality

[4]Highway construction cost is sunk.

[5]Values for ω_0 and ω_1 are calculated according to the time cost at the free flow and at the CBD. we take the value of 2.82 for γ, which is found in Yoshida (2011)

[6]We do not consider the fare for the monorail because its impact on the total system cost is identical to the reduction of toll given the price-inelastic demand.

[7]Specifically, they are such that $\tau = \gamma(m - \omega_0)/(\gamma + 1)$ and $Q_A = [\omega_1(\gamma + 1)/(m - \omega_0)]^{-1/\gamma}$.

Table 1: Parameter values of fundamental variables.

Parameter	*Values*	*Data Source*
Value of Time	479 Rs./h	*Feasibility Study of Skytrain Sri Lanka*
Monorail Speed	40 km/h	*Feasibility Study of Skytrain Sri Lanka*
Free-Flow Auto Speed	60 km/h	*Feasibility Study of Skytrain Sri Lanka*
Minimum Auto Speed	8 km/h	*Feasibility Study of Skytrain Sri Lanka*
Social Interest Rate	6 %	*Central Bank of Sri Lanka*

holding in the optimum.

The optimum occurs at the point where the total cost is minimized with respect to the monorail length $\bar{x}$, which implies

$$-\frac{\partial C}{\partial \bar{x}} = M'(\bar{x}) + F'(K)\,Q'(\bar{x}) \tag{1}$$

where the left-hand side is $(c(\bar{x}) - m)\,Q(\bar{x}) + \tau Q_A(\bar{x})$, which is the VTTS of commuters from monorail extention of a unit distance plus the toll revenue to the transport authority.[8] In this scenario, just outside of the monorail terminal the user cost for the driver is much higher than that for the monorail users. Therefore, a large number of drivers will shift to the monorail to balance the user cost difference. This creates an opportunity to build a park-and-ride facility.

3 Numerical Analysis

Parameter Settings Table 1 presents the parameter values of the basic variables, of which social interest rate is obtained from Central Bank of Sri Lanka while others are from the feasibility study of the monorail project.

Population density is converted to employment density by multiplying the labor force participation rate as 53.6% and the employment rate as 95.6% to the population aged 15 to 60.[9] We assume that employment density is exponentially decreasing over the distance, such that $E(x) = \alpha e^{-\beta x}$ where α and β are positive parameters that are estimated from the actual data along the west corridor of Sri Lanka. The estimation result of $E(x)$ yields $\alpha = 4,276$ and $\beta = 0.0934$, and these yields the commuting volume as

$$Q(x) = \frac{\theta\alpha}{\beta^2}(\beta x + 1)\,e^{-\beta x}$$

where the angle θ is set to be $\pi/6$, reflecting the fact that the western part of Colombo city is bounded by the ocean and there are seven corridors evenly distributed. From the above, we know that the number of commuters at the CBD $Q(0)$ is 256 thousand.

[8] As for the second term in the right hand side we use that $Q_M = Q - Q_A$ while Q_A is constant for all $x \leq \bar{x}$.

[9] These values are from the Department of Census and Statistics in Sri Lanka (2014).

We calculate the total benefit of the project as the net present value (NPV) of the aggregate travel time savings for 30 years, taking 240 working days per year, an exchange rate of 1 USD = 132.61 Rs., and a social interest rate of 6%. We assume that the monorail's cost M is increasing in the length of monorail with marginal extention cost being constant at say μ, i.e., $dM(\bar{x})/d\bar{x} = \mu$, and that the marginal construction cost of the park-and-ride facility is constant ϕ with respect to its capacity i.e., $dF(K)/dK = \phi$.

3.1 Current Situation Without Monorail

Prior to introduction of the monorail, all commuters drive on the highway to the CBD where no toll is in place. This scenario describes the current situation such that with a commuting volume of 256 thousand the speed on the highway is down to 8.0 km/h resulting in the maximum user cost of 59.9 Rs./km and an MEC of 146 Rs./km at the CBD. For this benchmark situation, the aggregate travel time cost (ATTC) is calculated to be 162 million Rs./day. At the same time, the results reveal that a driver who starts to travel 30 km away from the CBD has to spends 99.1 minutes on the road, and has a trip price of 791 Rs.

3.2 The Benchmark Case of Monorail at 40 km/h Speed with Optimal Congestion Toll

Here, we consider the introduction of a monorail by the side of the existing highway, running at an average speed of 40 km/h. Hence its user cost is 11.98 Rs./km along the monorail, and the automobile user cost is 11.98 Rs./km inclusive of the toll as well, with optimal toll being 2.95 Rs./km for any $x \leq \bar{x}$. These values for the user costs imply that there will be 192 thousand monorail users and 64 thousand drivers at the CBD after the monorail installation.

In the feasibility study, the monorail cost is given as 46.8 million USD/km, and the park-and-ride facility cost as 9.2 thousand USD per vehicle space.[10] The optimal length of the monorail in this scenario is 26.3 km. Auto speed at the CBD is greatly improved to be 53.1 km/h. For a 30km journey into CBD, automobile trip time is now only 34.0 minutes and the trip price is 349 Rs. inclusive of the toll. The aggregate travel time cost becomes 57 million Rs./day, and the net present value of resulting ATTS is 2.76 billion USD.[11] The total construction cost in turn is 1.34

[10] It is given in Japanese yen and the exchange rate of 120 yen/USD is used here.

[11] If instead the foreign aid is available to finance the monorail costs in the form of grant, and so it is outside of transport authority's consideration, then the monorail is constructed to the point where the user cost of the monorail and highway become equal, or, $\partial C/\partial \bar{x} = 0$. This point occurs at a distance of 28.8 km from the CBD. Note that in this scenario, because the user costs of driving and using the monorail are equal at the monorail terminal, no commuters will switch from automobile to monorail, and hence there is no need for park-and-ride facility at the monorail terminal. According to this setup, the aggregate travel time cost is slightly lower compared to the benchmark situation but the difference is negligible. This is because in equation (1), the impact of the park-and-ride facility $F'Q'$ is substantially larger than that of the marginal monorail extention cost $dM/d\bar{x}$.

billion USD, of which 1.23 billion is for monorail costs and 109 million is for the park-and-ride facility construction. Park-and-ride capacity is 11.9 thousand car spaces. Table 1 presents these results along with the results of sensitivity analyses in the following section.

3.3 Sensitivity Analyses

Slower Monorail Speed at 30km Deviating from the benchmark case as in the previous section, we investigate an alternative that the monorail speed is slower at 30km/hour. Optimal length becomes slightly shorter and is now 25.1km. There will be 82 million drivers at the CBD while 174 million passengers arrive at the CBD by the monorail. Auto speed at CBD will be reduced to 47.6 km/h and the ATTC is increased to 67 million Rs./day. NPV of ATTS is 2.5 billion while the total cost is 1.18, implying the b/c ratio of 2.1. Trip time for a 30km journey by auto is now 10% longer and is 37.4 minutes. Total toll revenue is more than twice as large as that in the benchmark case at 12.14 million Rs./day, which is due to the increased number of drivers as well as the higher toll level. Park-and-ride facility is not to be constructed, since the cost of extending a monorail is smaller than its cost saving from reduction in the park-and-ride facility capacity.

Doubling the Value of Time When the value of time is doubled to be 958 Rs./h reflectign the recent income growth, the optimal length of monorail is slightly longer to be 26.4 km. The allocation of drivers and monorail users do not change from the benchmark case, and hence the auto speed at CBD is the same. ATTC is twice as much and so is the NPV of ATTS. This implies that in equation (1), the marginal benefit of extending a monorail by unit distance in terms of ATTS$-\partial C/\partial \bar{x}$ is twice as much as before for the same $\bar{x}$. In turn the total cost is just as before, and hence M and F are the same. However, under this scenario $-\partial C/\partial \bar{x}$ is still as small as 0.66 million USD/km in terms of NPV, while the cost savings from reduced park-and-ride capacity by extending the monorail $F'Q'$ is as large as 46.2 million USD/km, which together account for the marginal monorail extention cost of 46.86 million USD/km at the optimal length. This results in the modest increase in the optimal monorail length, and therefore all the nominal variables such as trip price and total toll revenue are almost twice as much as before.

Population Increase or Decrease by 10% We now analyze the case such that the city's population is increased by 10%. That is, the population density is now 10% higher everywhere, and so is the employment density. This results in a longer optimal length of the monorail at 27.9km with the number of monorail users being 217.8 thousand at the CBD. Since the equilibrium user

Table 2: Results of numerical analysis.

Parameter	*Benchmark*	*30 km/h Monorail Speed*	*958 Rs./h Value of Time*	*+10% Popuation*	*-10% Popuation*
Optimal length of the monorail (km)	26.3	25.1	26.4	27.9	24.4
Number of drivers at CBD (thousand)	64.2	82.1	64.2	64.2	64.2
Number of monorail users at CBD (thousand)	192.2	174.3	192.2	217.8	166.6
Auto speed at CBD (km/h)	53.1	47.6	53.1	53.1	53.1
ATTC (million Rs./day)	57.0	67.0	114.0	63.4	50.7
NPV of ATTS (billion USD)	2.76	2.50	5.53	4.08	1.78
Total cost (billion USD)	1.34	1.18	1.34	1.41	1.26
Auto trip time for 30km (minutes)	34.0	37.4	34.0	34.0	34.0
Trip price (Rs.)	349	447	698	354	343
Total toll revenue (million Rs./day)	4.97	12.14	9.98	5.28	4.61
Park-and-ride capacity (thousand)	11.9	0	11.3	10.7	13.4

cost is still the same where the monorail is available the number of drivers at the CBD is still 64.2 thousand and the auto speed is 53.1 km/h, the same as the benchmark case. ATTS is as large as 4.08 million USD and the total cost is 1.41, resulting in the benefit cost ratio of 2.89, which is much larger than 2.06, the ratio in the benchmark case.

If in turn the population is decreased by 10%, then the optimal length is reduced to be 24.4km with the number of users being 166.6 thousand at the CBD. The nuber of drivers and the auto speed at the CBD are still the same as the benchmark case. The NPV of ATTS is down to 1.78 million USD, which is just 1.41 times larger than the total cost.

Appendix

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Table 3: Results of numerical analysis.

Parameter	*Benchmark*	$\gamma = 4.0$	$\gamma = 1.5$	*5% Social Interest Rate*	*7% Social Interest Rate*
Optimal length of the monorail (km)	26.3	23.6	28.6	26.3	26.3
Number of drivers at CBD (thousand)	64.2	90.3	25.2	64.2	64.2
Number of monorail users at CBD (thousand)	192.2	166.1	231.2	192.2	192.2
Auto speed at CBD (km/h)	53.1	54.5	50.0	53.1	53.1
ATTC (million Rs./day)	57.0	53.8	62.9	57.0	57.0
NPV of ATTS (billion USD)	2.76	2.37	3.56	3.06	2.51
Total construction cost (billion USD)	1.34	1.11	1.71	1.34	1.34
Auto trip time for 30km (minutes)	34.0	32.7	36.8	34.0	34.0
Trip price (Rs.)	349	336	362	349	349
Total toll revenue (million Rs.)	4.97	6.85	1.72	4.97	4.97
Park-and-ride capacity (thousand)	11.9	0	39.9	11.8	11.9

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