Environmental Sustainability or Equity in Welfare?

Analysing Passenger Flows of a Mass Rapid Transit System with Heterogeneous Demand

Varun Varghese

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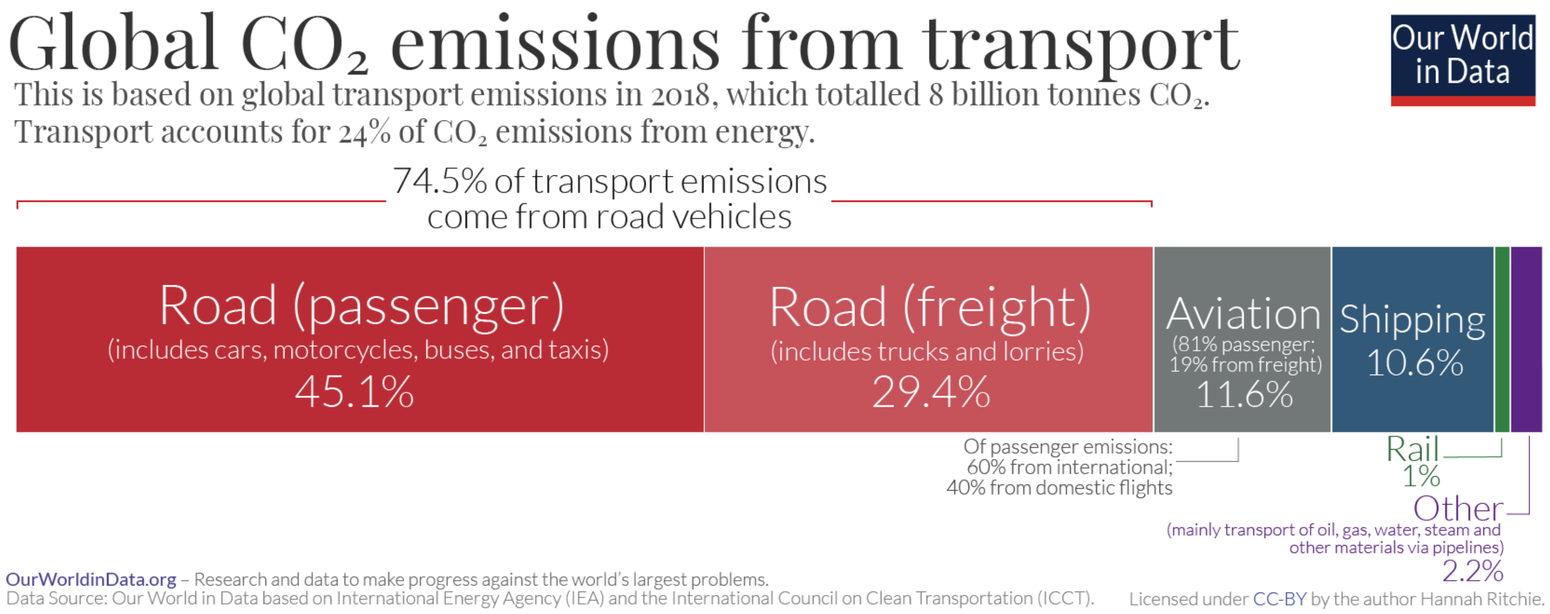
Environmental sustainability

Transportation produces roughly 24 percent of the global CO2 emissions from fuel combustion (IEA and ICCT data)

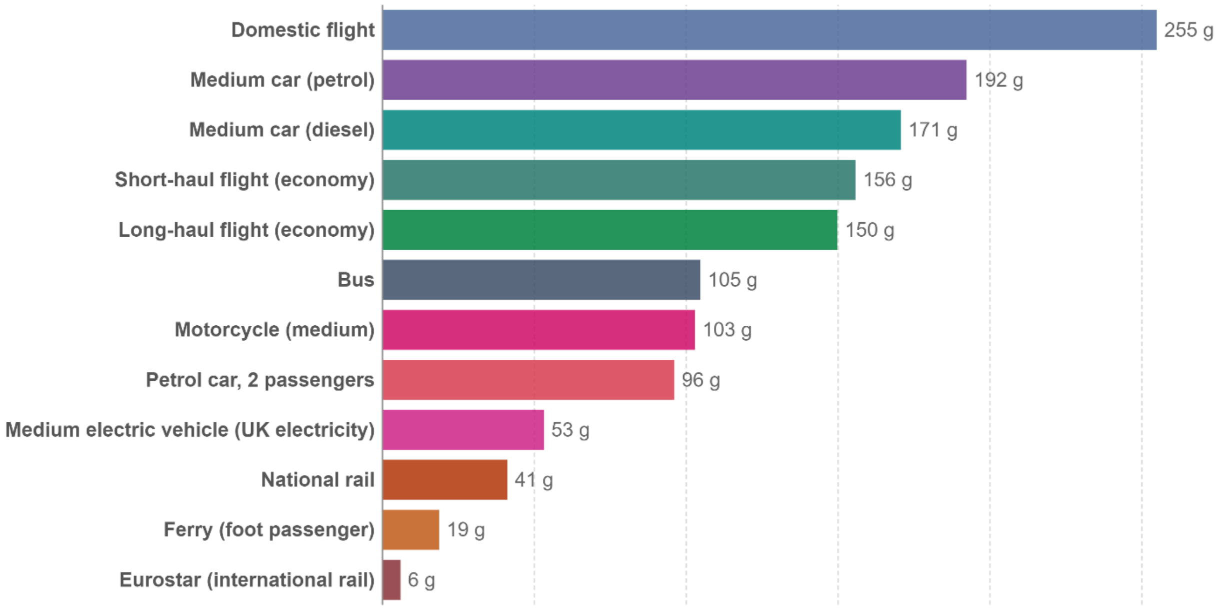


Reducing CO_2 emissions is a part of a wider move towards greater sustainability

Private vehicle use and CO_2 emissions

Carbon footprint of travel per kilometer, 2018

The carbon footprint of travel is measured in grams of carbon dioxide-equivalents[1] per passenger kilometer. This includes the impact of increased warming from aviation emissions at altitude.



Source: UK Department for Business, Energy & Industrial Strategy. Greenhouse gas reporting: conversion factors 2019.
Note: Data is based on official conversion factors used in UK reporting. These factors may vary slightly depending on the country, and assumed occupancy of public transport such as buses and trains.

1. Carbon dioxide-equivalents (CO_2eq): Carbon dioxide is the most important greenhouse gas, but not the only one. To capture all greenhouse gas emissions, researchers express them in 'carbon dioxide-equivalents' (CO_2eq). This takes all greenhouse gases into account, not just CO_2. To express all greenhouse gases in carbon dioxide-equivalents (CO_2eq), each one is weighted by its global warming potential (GWP) value. GWP measures the amount of warming a gas creates compared to CO_2. CO_2 is given a GWP value of one. If a gas had a GWP of 10 then one kilogram of that gas would generate ten times the warming effect as one kilogram of CO_2. Carbon dioxide-equivalents are calculated for each gas by multiplying the mass of emissions of a specific greenhouse gas by its GWP factor. This warming can be stated over different timescales. To calculate CO_2eq over 100 years, we'd multiply each gas by its GWP over a 100-year timescale (GWP100). Total greenhouse gas emissions – measured in CO_2eq – are then calculated by summing each gas' CO_2eq value.

Who uses cars?

- Differences exist between the developed world and the global south
- Car use is more prevalent in the higher income groups in the global south
- Car is perceived as a symbol of status, 61% of respondents agree to the statement that ***car make them feel that they are doing well in their life*** (Verma, M., 2015).
- How to shift these users to public transport?

Equity in welfare

Dictionary

Definitions from Oxford Languages · Learn more

equity

noun

1. the quality of being fair and impartial.
   "equity of treatment"

   Similar: fairness fair-mindedness justness justice equitableness fair play

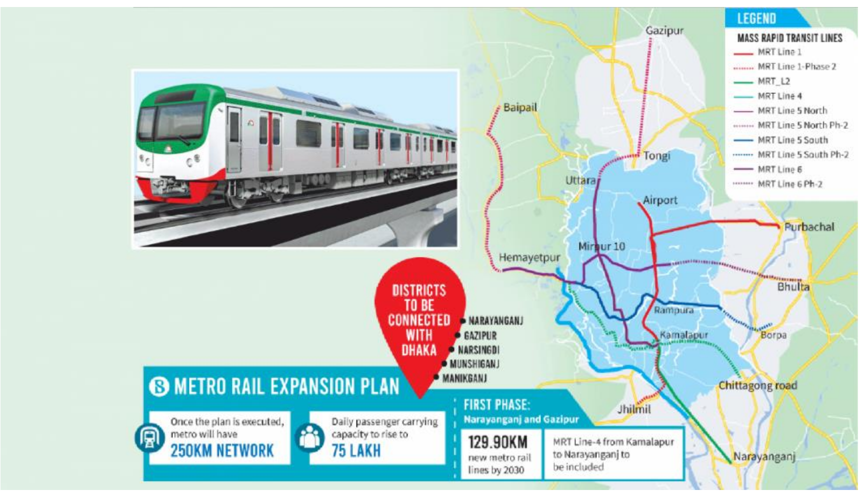


Image source:
https://www.tbsnews.net/

The benefits of a new transportation system may include :

- Increases access to many opportunities including jobs
- Saved travel time
- Decrease in CO_2 emissions

How to ensure that these benefits are distributed fairly?

Environmental sustainability and equity through the crowding lens

Introducing a public transport (PT) system has many goals:

- Reduction in disparities by providing a better transport option to lower income people
- Improvement of environmental sustainability by reducing car use

When PT at low fare make many opportunities available to people

When car users (typically higher income people in the global south) shift to PT

How people **value crowding** might depend on income
e.g., people with higher income would be willing to pay a higher price for their desired comfort or to reduce their travel time during crowded situations

There could be a trade-off between the improvement of environmental sustainability (by the reduction of car use) and the improvement of equity (more people belonging to the low-income group use PT)

Crowding and heterogeneities in mode choice

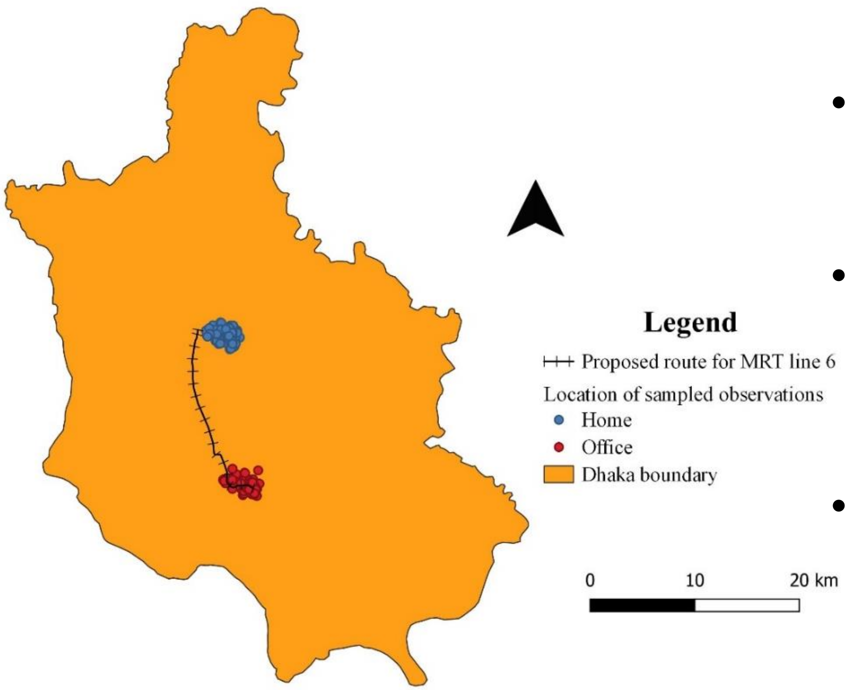
- **Crowding** is one of the major roadblocks hampering the **attractiveness** of **public transport systems**.
- Crowding has also been used as a variable to test its effect on public transport route choice, public transport fare optimization, waiting time, travel time reliability, and wellbeing of travelers.
- An area of research which has not received enough attention is the **analysis of the heterogeneities in the effects of crowding** due to socio-economic disparities. Especially, in **developing economies**.
- Moreover, these heterogeneities in the effects will also lead to **heterogeneities in actual demand for the public transport mode** and evaluating that is pivotal for policymakers.

Research objectives

- Analyzing the **sensitivity towards crowding** in mode choice behaviour of travelers based on their income.
  - We employ error components based Mixed Logit Models (ML) to achieve this objective by using data from Dhaka, Bangladesh

- Implementing a fare- and capacity-based scenario analysis to **estimate equilibrium passenger flow** for each income group and confirm how fare and capacity settings of the Dhaka metro system could influence **ridership and social welfare** of the users.
  - We employ the stochastic user equilibrium condition to estimate equilibrium passenger flows while accounting for the heterogeneity in the effect of crowding across different income groups. We try to quantify the trade-off between reduction in car use and improvement of equity in welfare.

Study area



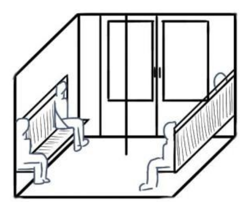
- Dhaka is one of most dense cities of the world.
- High income disparity and high levels of congestion
- MRT system is expected to relieve the congestion and environmental pollution
- MRT line 6 started operations from 2022. The line connects Ashulia to Kamalapur via Uttara Phase 3, Pallabi, Tejigaon, and Motijheel.

- We fix the origin and destination of our survey and interview people living in Uttara Phase 3 and working in Mothijeel

SP survey

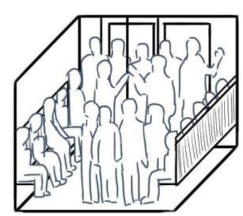
Variables	Levels
Travel Time (min)	30, 40, 50
Fare (BDT)	70, 150, 300
Frequency of Services (min)	4, 7,10
Crowding Level (as mentioned)	1, 2, 3, 4, 5, 6

Crowding level	Density of standing passengers (pax/m²)	Occupancy level % (v/k)
1	0	20 (0.2)
2	3	100 (1.0)
3	6	150 (1.5)
4	8	200 (2.0)
5	10	250 (2.5)
6	12	300 (3.00

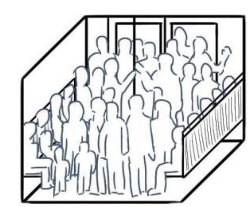

Crowding Level-1


Crowding Level-2


Crowding Level-3

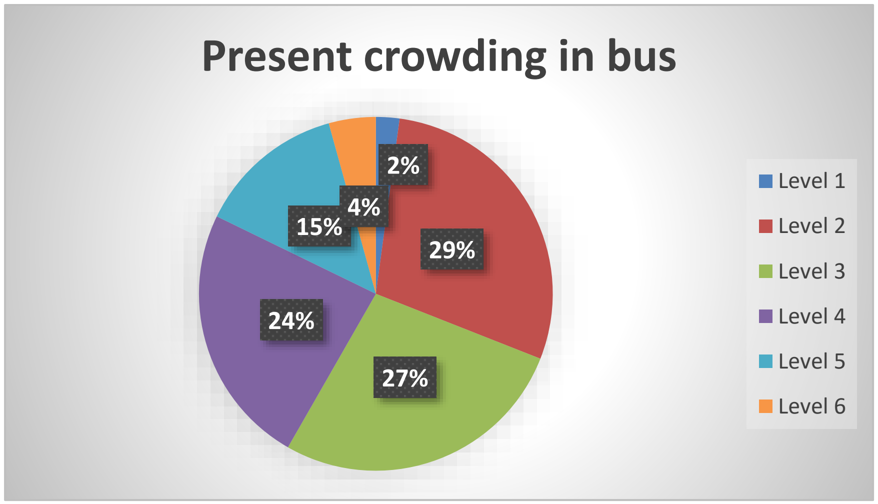

Crowding Level-4


Crowding Level-5

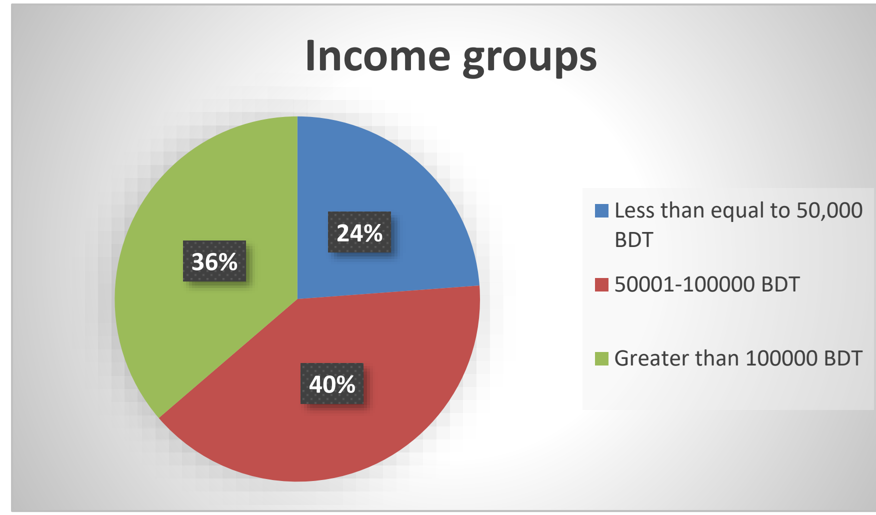

Crowding Level-6

A fractional orthogonal design resulted in a total of 18 sets of variations, of which six were presented to every person randomly. Therefore, a total of 2125 responses were recorded for 361 respondents after a through data cleaning process.

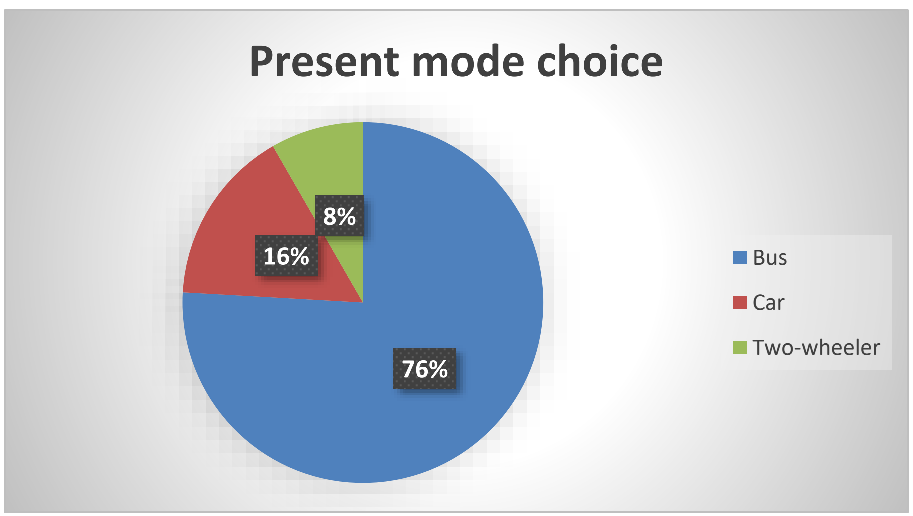
Data



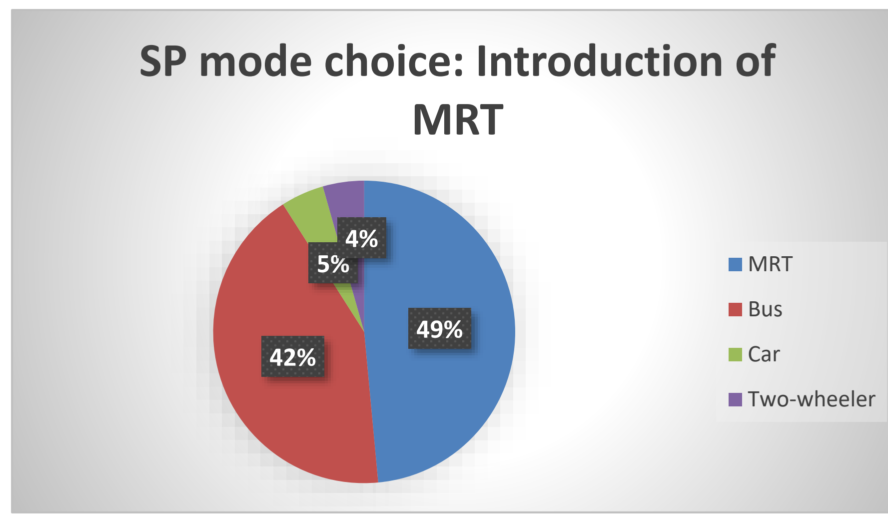
Present crowding in bus
2%
4%
15%
29%
24%
27%
Level 1
Level 2
Level 3
Level 4
Level 5
Level 6



Income groups
24%
36%
40%
Less than equal to 50,000 BDT
50001-100000 BDT
Greater than 100000 BDT



Present mode choice
8%
16%
76%
Bus
Car
Two-wheeler



SP mode choice: Introduction of MRT
4%
5%
49%
42%
MRT
Bus
Car
Two-wheeler

Crowding as a dummy variable

$$U_{tij} = asc_j + \beta_{TT} * TT_{tj} + \beta_{HW} * HW_{tj} + \beta_{TC} * TC_{tj} + \sum_{k=2}^{6} \beta_{CL,k} * CL_{tjk} * TT_{tj} + ec_{ij} + \varepsilon_{tij}$$

j ∈{MRT, Bus, Car, Two-wheeler}

U_{tij}: Random utility of an individual i for choosing an alternative j under SP scenario t

asc_j: Alternative specific constant specific

β_{TT}: Parameter for travel time

β_{TC}: Parameter of travel cost

$\beta_{CL,k}$: Parameter for crowding level k (k

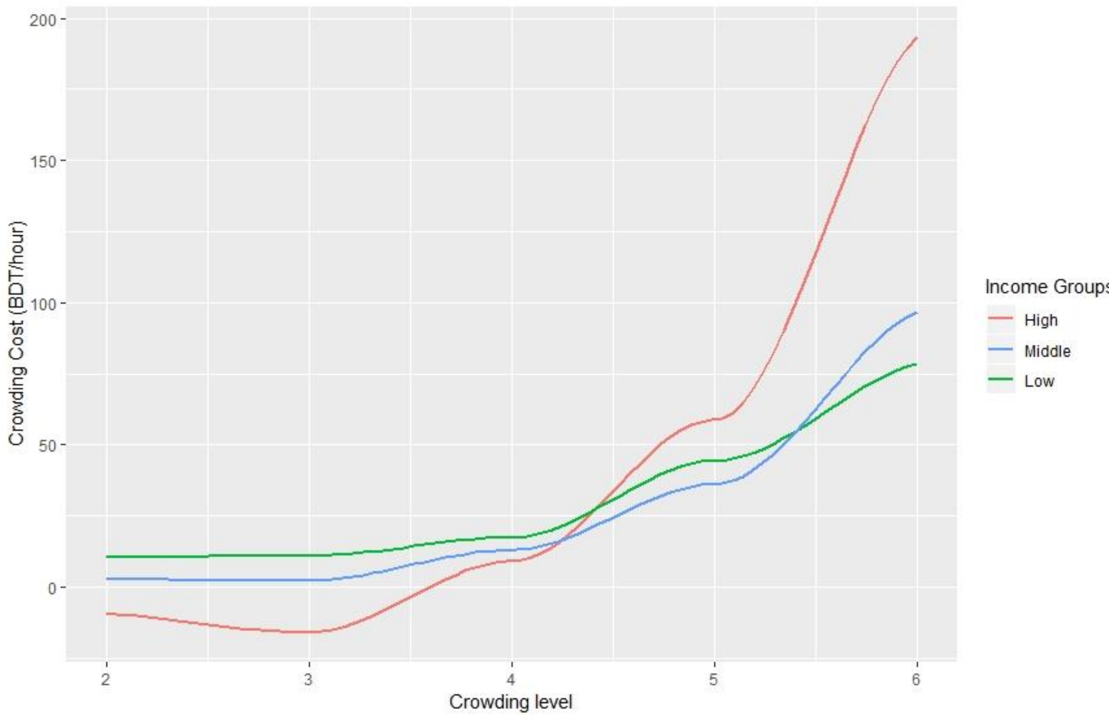
TT_{tj}: Travel time for alternative j under S

HW_{tj}: Headway for alternative j under SP

TC_{tj}: Travel cost for alternative j under S

ec_{ij}: Individual-specific error component with mean 0 and variance σ^2

ε_{tij}: White noise, following the standard (



CL_{tjk}: 1: if the crowding level is k for alternative j under scenario t; 0 otherwise

Mixed logit results: Crowding as a dummy variable

	High income		Middle Income		Low income		Whole sample	
	Estimate	t stat	Estimate	t stat	Estimate	t stat	Estimate	t stat
Asc MRT	4.00	2.21	3.60	2.72	0.81	0.72	2.63	3.46
Asc Bus	0.79	0.42	2.60	1.97	1.05	0.49	1.48	1.92
Asc Car	3.32	2.32	12.69	7.87	--	--	6.25	5.72
Travel time	-1.11	-1.15	-0.48	-0.65	-0.01	-0.68	-0.58	-1.17
Fare	-0.03	-8.19	-0.04	-10.44	-0.04	-6.69	-0.04	-16.03
Headway	-0.44	-4.75	-0.21	-4.44	-0.17	-3.1	-0.24	-7.67
Crowding level 2	0.32	0.44	-0.10	-0.2	-0.46	-0.67	-0.14	-0.42
Crowding level 3	0.54	0.73	-0.09	-0.17	-0.49	-0.71	-0.18	-0.51
Crowding level 4	-0.31	-0.42	-0.51	-0.93	-0.77	-1.1	-0.45	-1.32
Crowding level 5	-1.98	-2.63	-1.40	-2.63	-1.96	-2.26	-1.39	-3.87
Crowding level 6	-6.52	-5.47	-3.77	-4.65	-3.48	-3.87	-4.02	-7.75
Sigma MRT	3.50	4.75	2.95	4.62	2.60	4.7	3.00	7.84
Sigma Bus	5.39	5.06	1.72	1.85	0.18	0.16	1.39	2.05
Sigma Car	7.05	5.8	8.71	8.75	--	--	12.82	11.57
LL0	-600.392		-651.091		-366.009		-1617.492	
LL final	-305.729		-388.428		-177.545		-929.585	
AIC	639.46		804.86		379.09		1887.17	
#individual	124		151		86		361	
#observation	729		882		514		2125	

Crowding as a continuous variable

$$U_{ij} = asc_j + \beta_{tt} * TT_j + \beta_{hw} * HW_j + \beta_{tc} * TC_j + \boxed{\gamma \left(\frac{v_j}{K_j}\right)^{\rho}} * TT_j + ec_{ij}$$

v_j = actual number of passengers in the coach for alternative j

K_j = normal capacity of the coach for alternative j

γ = scale parameter associated with crowding disutility

ρ = shape parameter associated with crowding disutility

A BPR-type function

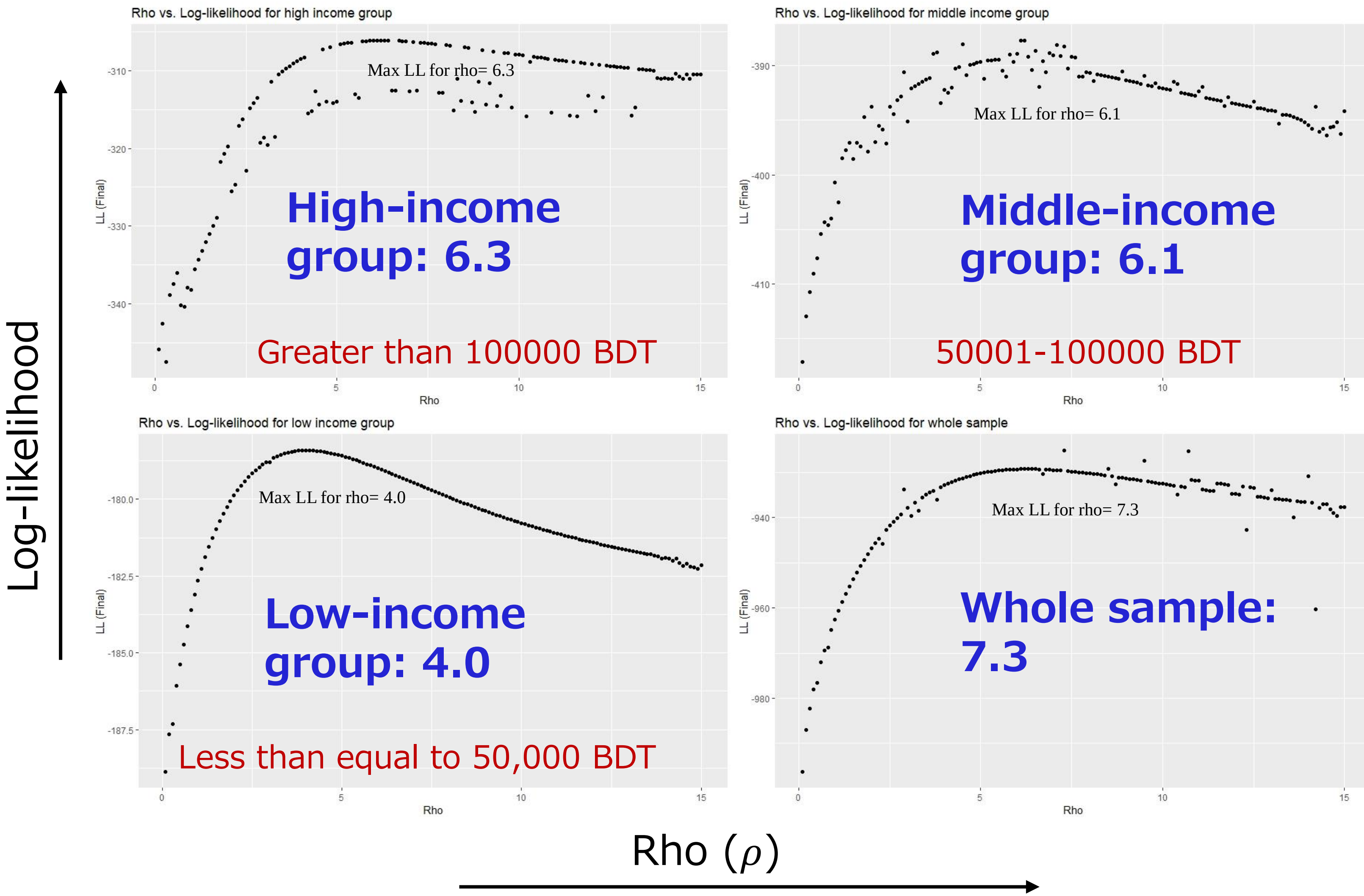
$$P_{tij} = \int_{ec_{ij}} \frac{a_{ij} \cdot \exp\left(V_{tij} + ec_{ij}\right)}{\sum_{j=1}^{J} a_{ij} \cdot \exp\left(V_{tij} + ec_{ij}\right)} f\left(ec_{ij}|\sigma\right) \mathrm{d}ec_{ij}$$

P_{tij}: probability of an individual i for choosing an alternative j under SP scenario t

a_{ij}: availability of alternative j for individual i

$f(\cdot)$: normal distribution with mean 0 and variance σ^2

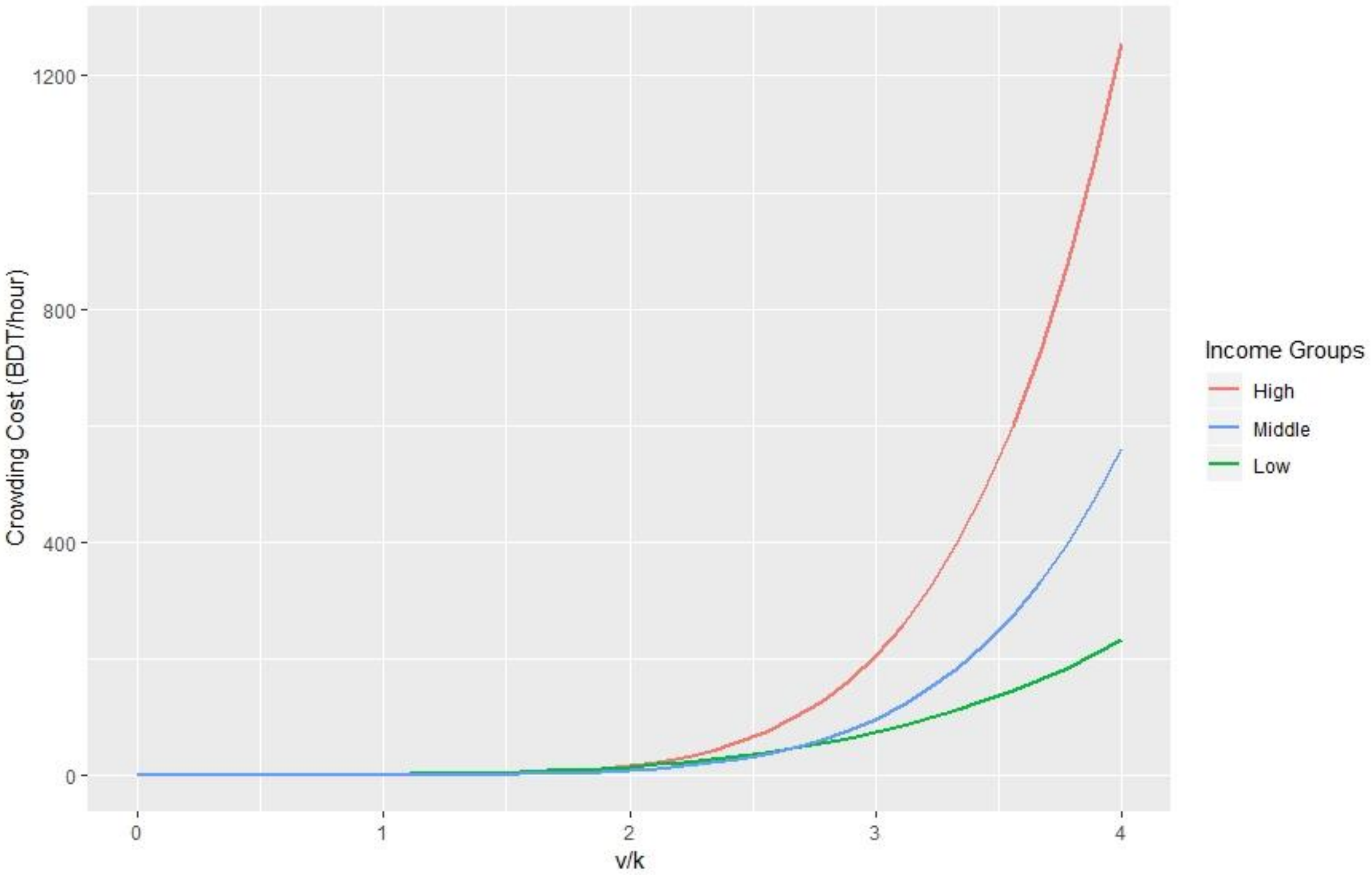
Grid search to calculate ρ



Mixed logit results: Crowding as a continuous variable

	High income		Middle Income		Low income		Whole sample	
	Estimate	t stat	Estimate	t stat	Estimate	t stat	Estimate	t stat
Asc MRT	4.32	2.85	3.67	3.41	0.57	0.47	2.90	4.44
Asc Bus	1.30	0.74	2.87	2.83	-0.59	-0.45	1.60	2.36
Asc Car	3.11	1.99	8.84	3.94			4.72	4.95
Travel time	-0.73	-0.94	-0.66	-1.14	-0.37	-0.5	-0.74	-1.8
Fare	-0.03	-8.14	-0.04	-10.28	-0.04	-6.79	-0.04	-16.19
Headway	-0.43	-5.1	-0.22	-4.37	-0.18	-3.19	-0.24	-7.69
Gamma (γ)	-0.0068	-6.77	-0.0046	-6.27	-0.0399	-4.95	-0.0013	-9.71
Sigma MRT	3.42	5.25	2.78	5.71	2.60	4.71	2.81	8.36
Sigma Bus	5.33	5.52	1.93	3.24	0.29	0.26	2.06	4.7
Sigma Car	7.12	6.08	10.036	7.24			10.15	11.95
LL0	-600.392		-651.091		-366.009		-1617.492	
LL final	-306.150		-387.712		-178.407		-925.093	
AIC	632.3		795.42		372.81		1870.19	
#individual	124		151		86		361	
#observation	729		882		514		2125	

Crowding cost



Stochastic user equilibrium (SUE) approach

$$x_{n,m} = x_{n-1,m} + \frac{1}{n}(y_{n-1,m} - x_{n-1,m})$$

where,

$x_{n,m}$ = Metro flow at the n^{th} iteration for the m^{th} income group; a value of $x_{0,m}$ is allocated at the first iteration to calculate $x_{1,m}$

$y_{n-1,m}$ = Updated flow using the utility equation $U_{n-1,m}$ and the consecutive probability of choosing MRT system ($P_{ti,MRT}(x_{n-1,m}) \cdot \tau_m$, where τ_m represents the total number of commuters belonging to income group m). Meanwhile, $U_{n-1,m}$ itself is a function of flow at the $n-1^{\text{th}}$ iteration.

$$U_{\text{n}-1,m} = f(x_{\text{n}-1,m})$$

$$x_{n,metro} = \sum_{\text{m}=1}^{\text{M}} x_{\text{n},m}$$

The iterations are continued until total passenger flow $x_{n,metro}$ reaches an equilibrium value

User surplus

$$LS_m = \frac{1}{I}\sum_{i=1}^{I}\int_{ec_{ij,m}} \ln\left(\sum_{j=1}^{J} a_{ij} \cdot \exp\left(V_{ij,m} + ec_{ij,m}\right)\right) \mathrm{d}ec_{ij,m}$$

Where, LS_m= Average log-sum for income group m and

$V_{i,k,j}$ = Observed part of the utility for alternative i and individual j belonging to income group m calculated for the equilibrium flow.

User surplus (US_j) for each income group was then calculated at the equilibrium flows using the following formulation

$$US_m = \frac{1}{\beta_{TC}}\left[\frac{1}{I}\sum_{i=1}^{I}\int_{ec_{ij,m}} \ln\left(\sum_{j\in\{\text{MRT,Bus,Car,Two-wheeler}\}} a_{ij} \cdot \exp\left(V_{ij,} + ec_{ij,m}\right)\right) \mathrm{d}ec_{ij,m} - \frac{1}{I}\sum_{i=1}^{I}\int_{ec_{ij,m}} \ln\left(\sum_{j\in\{\text{ Bus,Car,Two-wheeler}\}} a_{ij} \cdot \exp\left(V_{ij,m} + ec_{ij,m}\right)\right) \mathrm{d}ec_{ij,m}\right]$$

Total consumer surplus

$$CS_{total} = \sum_{\mathrm{m}=1}^{\boldsymbol{M}} \tau_{\boldsymbol{m}} US_{\boldsymbol{m}}$$

where,

CS_{total}= Total consumer surplus

τ_m= Total number of commuters belonging to income group m

The calculations were made by varying the levels of fare and capacity (a function of headway and number of cars) and finally revenue for each scenario was calculated based on

$$Revenue = \sum_{m=1}^{M} \hat{x}_m \times fare_{metro,m}$$

where,

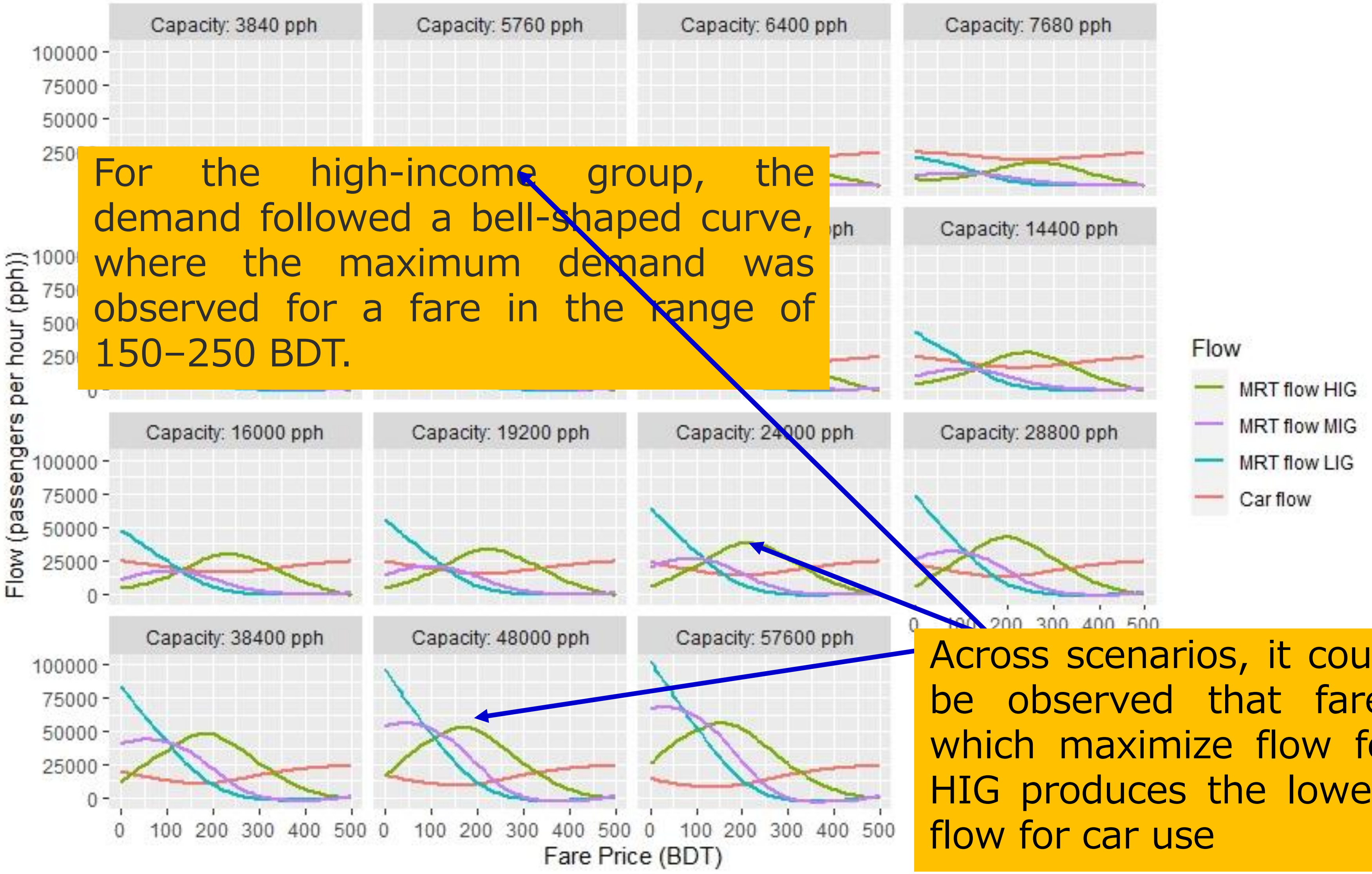
$\hat{x}_m$= Equilibrium metro flow for income group m

$fare_{metro,m}$= Fare of metro for income group m

Fare and capacity scenario analysis

Item Name	Item Description
Capacity	$= \frac{60}{headway_{metro}} \times no.of\ cars \times 160$ $headway_{metro}$ varies between 2, 4, 6, and 10 min $no.of\ cars$ or coaches varies between 4, 6, 8, 10, 12
Fare	Fare for each income group varies between 0, 10, 50, 100, 150, 200, 250, 300, 400, 450, 500 BDT
Peak hour passenger (number)	334,081 (JICA, 2015)
Distribution of passenger based on income-groups (number)	Low-income group (LIG) (44.10%) = 147,330 Middle-income group (MIG) (35.50%) = 118,599 High-income group (HIG) (20.40%) = 68,153
Bus capacity (number/hour)	It is assumed that bus service will maintain a crowding of 150% for all scenarios.
Road congestion	Road congestion has been ignored, i.e., road will have sufficient capacity to take care any number of traffic and no disutility will be induced from the congestion

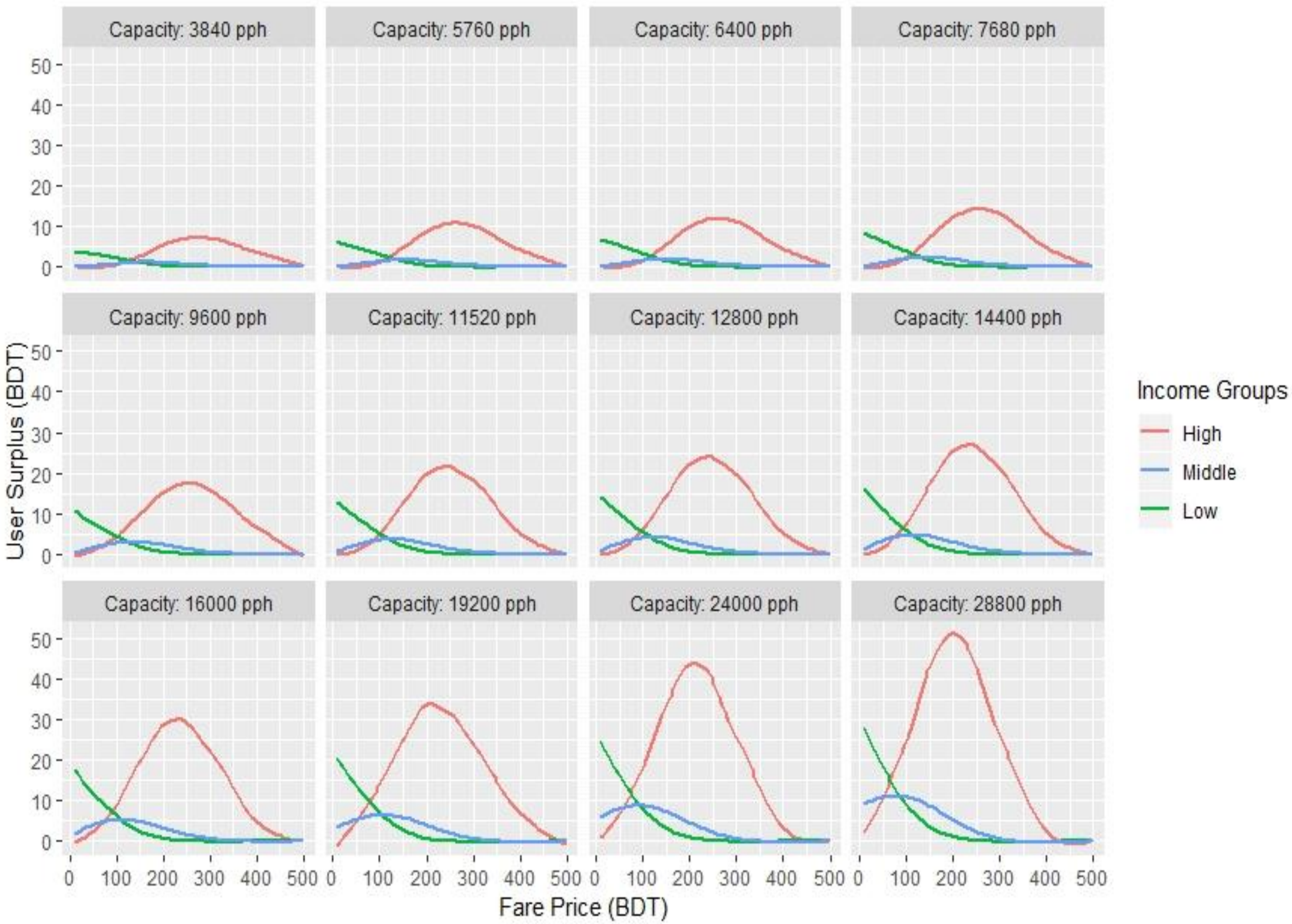
Metro flow



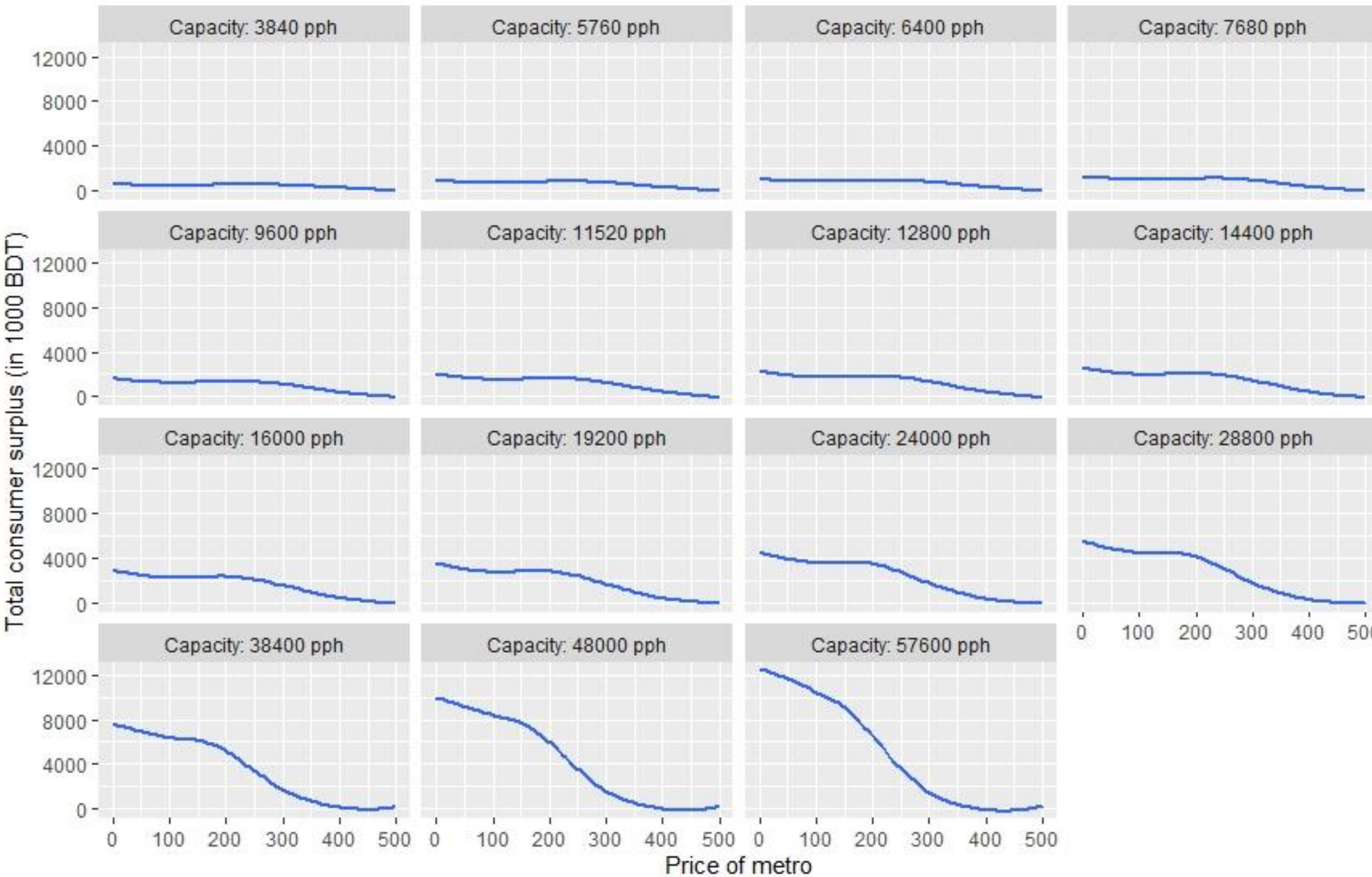
For the high-income group, the demand followed a bell-shaped curve, where the maximum demand was observed for a fare in the range of 150–250 BDT.

Across scenarios, it could be observed that fares which maximize flow for HIG produces the lowest flow for car use

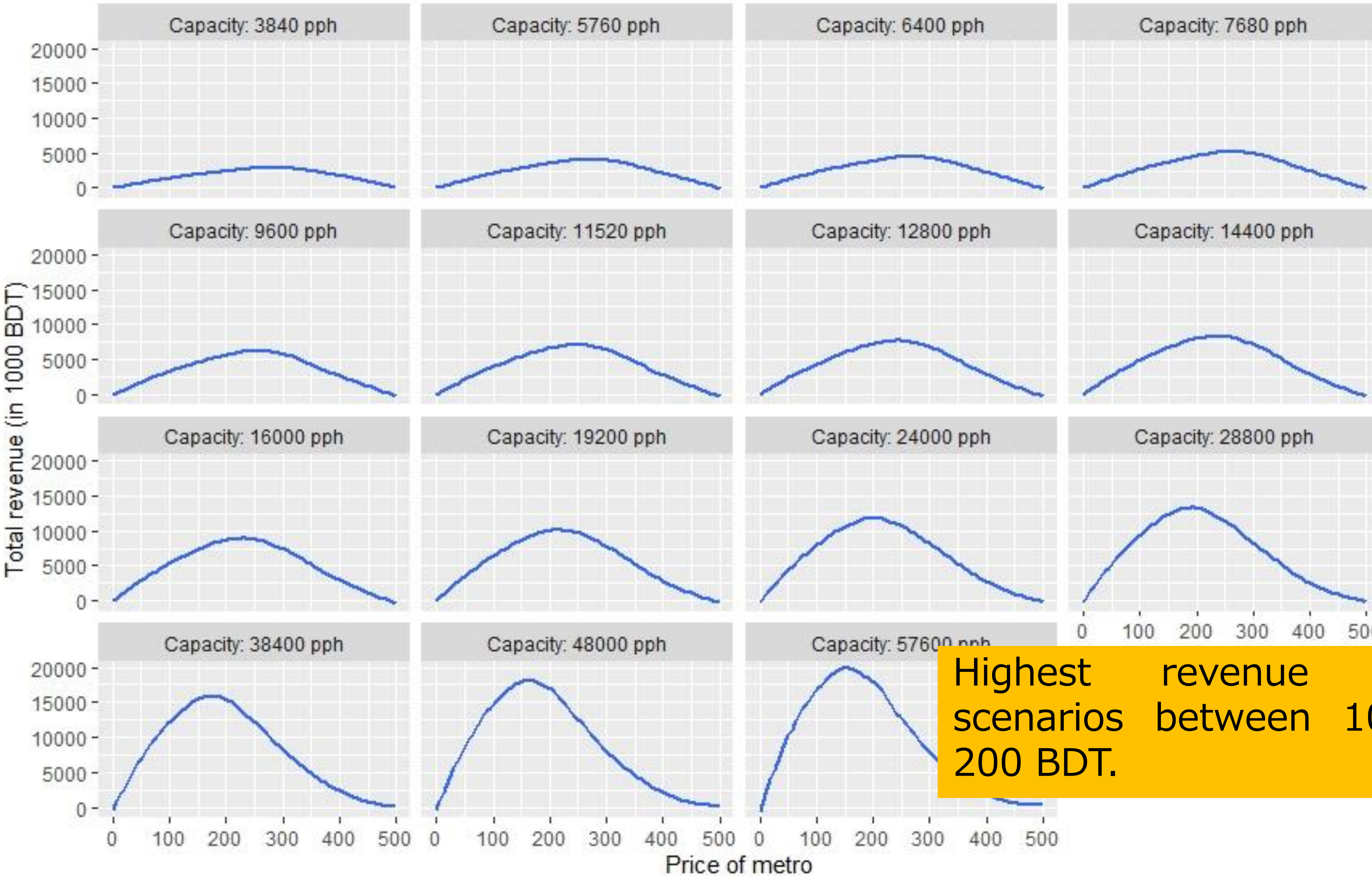
User surplus



Total consumer surplus



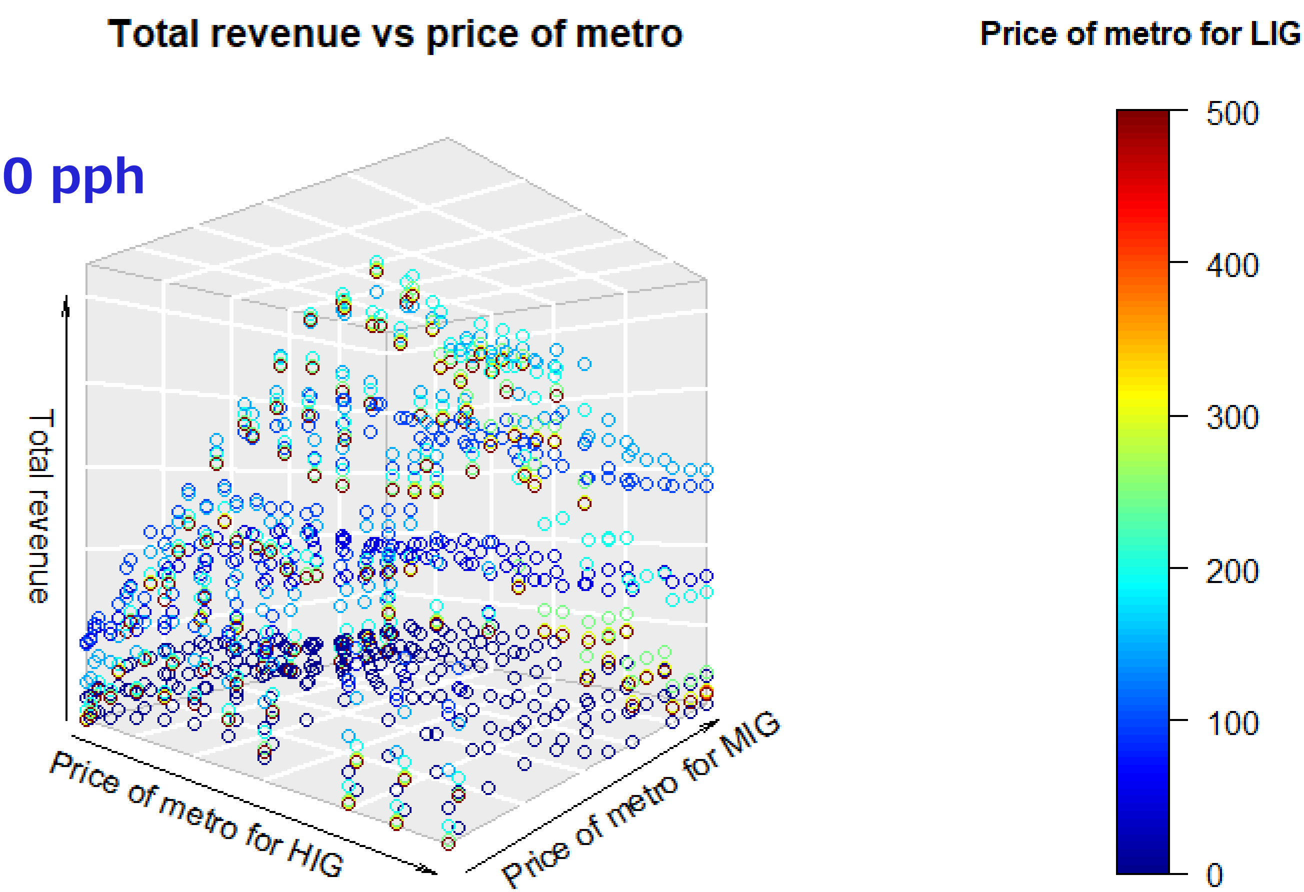
Revenue



Highest revenue for scenarios between 100-200 BDT.

Varying fare for income groups

Capacity 19200 pph



Maximum value for revenue when
Fare for HIG: 200; Fare for MIG : 150; Fare for LIG : 150
Capacity: 57,600 pph

Varying fare for income groups

For a variable pricing scheme with different fares across different income groups, highest social welfare was observed for the scenario whereby the fare for the low- and middle-income groups was in the higher range (150 BDT), resulting in lower MRT ridership among these groups.

The lowest levels of car use were observed in the scenario whereby the fare for both the high- and middle-income groups was low (10 BDT), so the MRT ridership for these groups was high, indicating a direct correlation between car use and MRT use among these income groups.

Objective function of metro fare setting	Capacity	Fare			Consumer surplus (BDT)	Revenue (BDT)	Total surplus (BDT)	MRT Flow			Car flow
		High income	Middle income	Low income				High income	Middle income	Low income	
Same fare											
Maximum consumer surplus (BDT)	57,600	10	10	500	19,523,592						
Maximum Revenue (BDT)	57,600	200	150	150	7,451,298	22,043,747	29,495,045	46,807	51,719	32,829	10,139
Maximum total surplus (BDT)	57,600	100	150	150	12,018,140	1,7805,076	29,823,215	62,721	47,328	29,558	6,707
Maximum flow											
High income	57,600	10	500	500	17,289,750	680,812	17,970,562	67,968	2	0	7,519
Middle income	57,600	500	10	500	16,220,879	1,391,890	17,612,769	459	116,230	0	16,804
Low income	57,600	500	500	10	13,361,994	1,514,284	14,876,278	289	1	136,922	24,056
Minimum car flow	57,600	10	10	500	19,523,592	1,697,801	21,221,393	62,552	107,228	0	2,738

Key take-aways

- People are sensitive to crowding based on their income
- When this sensitivity to crowding based on income group was accounted for while estimating the demand for the MRT system, it was observed that the demand was heterogenous across groups
- Fares which result in the highest social welfare are not equitable
- Equitable fares result in lower supplier benefits and higher car-use
- Car use related with MRT demand of high- and middle-income group
- Findings highlight the trade-off decisionmakers would have to make between having an equitable public transport system and reducing the use of private vehicles

Limitations

- We ignore road congestion;
- Income categories not truly representative of the region;
- Crowding in bus assumed to be constant;
- Access time, egress time, crowding at station etc.; have not been considered in the utility equations;
- Operator’s cost have not been considered

References

1. Singleton, Patrick A. Exploring the Positive Utility of Travel and Mode Choice. NITC-DIS-1005. Portland, OR: Transportation Research and Education Center (TREC), 2017 (Link: https://ppms.trec.pdx.edu/media/project_files/NITC_1005_Exploring_Positive_Utility_of_Travel.pdf)
2. De Vos, J., Singleton, P. A., & Gärling, T. (2022). From attitude to satisfaction: introducing the travel mode choice cycle. *Transport Reviews*, *42*(2), 204-221.
   (Link: https://www.tandfonline.com/doi/pdf/10.1080/01441647.2013.815665)
3. Ettema, D., Gärling, T., Eriksson, L., Friman, M., Olsson, L. E., & Fujii, S. (2011). Satisfaction with travel and subjective well-being: Development and test of a measurement tool. Transportation Research Part F: Traffic Psychology and Behaviour, 14(3), 167-175. (Link: https://www.sciencedirect.com/science/article/pii/S1369847810000847)
4. Bergstad, C. J., Gamble, A., Gärling, T., Hagman, O., Polk, M., Ettema, D., ... & Olsson, L. E. (2011). Subjective well-being related to satisfaction with daily travel. Transportation, 38, 1-15. (Link: https://link.springer.com/article/10.1007/s11116-010-9283-z)
5. Circella, G., Mokhtarian, P. L., & Poff, L. K. (2012). A conceptual typology of multitasking behavior and polychronicity preferences. Electronic International Journal of Time Use Research, 9(1). (Link: bit.ly/3Ytmn2a)
6. Lyons, G., & Urry, J. (2005). Travel time use in the information age. Transportation Research Part A: Policy and Practice, 39(2-3), 257-276. (Link: https://www.sciencedirect.com/science/article/pii/S0965856404000977)
7. Malichová, E., Van Acker, V., Cornet, Y., & Milakis, D. (2022). Worthwhile travel time: how do travel activities contribute to perceived values of travel time? Insights from European-wide app-based travel data.
   (Link: https://elib.dlr.de/193005/1/Malichova%20et%20al_TRA%202022.pdf)
8. Hess, S., Bierlaire, M., & Polak, J. W. (2005). Estimation of value of travel-time savings using mixed logit models. Transportation Research Part A: Policy and Practice, 39(2-3), 221-236. (Link: https://www.sciencedirect.com/science/article/pii/S0965856404001028)

References

9. Li, Z., & Hensher, D. A. (2013). Crowding in public transport: a review of objective and subjective measures. Journal of Public Transportation, 16(2), 10 7-134. (Link: https://www.sciencedirect.com/science/article/pii/S1077291X22012486#bib26)
10. Bhat, C. R. (2008). The multiple discrete-continuous extreme value (MDCEV) model: role of utility function parameters, identification considerations, and model extensions. Transportation Research Part B: Methodological, 42(3), 274-303. (Link: : https://www.sciencedirect.com/science/article/pii/S0191261507000677)
11. Varghese, V., & Jana, A. (2018). Impact of ICT on multitasking during travel and the value of travel time savings: Empirical evidences from Mumbai, India. Travel Behaviour and Society, 12, 11-22. (Link : https://www.sciencedirect.com/science/article/pii/S2214367X17301114)
12. Varghese, V., Chikaraishi, M., & Kato, H. (2020). Analysis of travel-time use in crowded trains using discrete-continuous choices of commuters in tokyo, Japan. Transportation Research Record, 2674(10), 189-198. (Link : https://journals.sagepub.com/doi/abs/10.1177/0361198120934794?journalCode=trra)
13. Varghese, V., Moniruzzaman, M., & Chikaraishi, M. (2022). Environmental sustainability or equity in welfare? Analysing passenger flows of a mass rapid transit system with heterogeneous demand. Research in Transportation Economics, 101258. (Link : https://www.sciencedirect.com/science/article/pii/S073988592200083X)
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Contact details
Varun Varghese, Ph.D.
Assistant Professor
Infrastructure Planning and Urban Risk Management Lab.
Graduate School of Advanced Science and Engineering, Hiroshima University
email: varunvarghese17@gmail.com; varunv@hiroshima-u.ac.jp
Research website: bit.ly/2UKuB7H

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