Innovative Methods Towards Building and Evaluating Congestion Charging Scenarios: The Case of Metro Vancouver[1]

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Introduction

This paper shares Metro Vancouver's approach towards studying congestion charging, and particularly the approaches used to build and evaluate a range of congestion charging scenarios. An independent commission was assembled in June 2017 with the task of studying mobility pricing and providing recommendations for the region by spring 2018. The Commission's recommendations were guided by three core objectives: reduce congestion, promote fairness, and support transportation investment. A number of innovative approaches were undertaken by the project team in order to further understand these objectives and fulfill the requirements of the Commission. This includes building, analysing, and evaluating the performance of a range of congestion charging scenarios. This work was a critical component towards informing the Commission's recommendations, which consist of a set of principles to help guide the development of a coordinated mobility pricing policy for Metro Vancouver, and some illustrative concepts of what a congestion charging system could look like that adheres to these principles and meets the Commission's objectives.

This paper is structured as follows: the next section provides an overview of the evaluation framework and analytical approach developed throughout the Commission's term. Following that, we describe how the theory of marginal social cost (MSC) pricing has been applied in practice in order to determine the congestion charge rates for the scenarios. The approach used to address some elements of fairness is then shared, before closing with a summary and conclusion.

Evaluation Framework and Analytical Approach

A rigorous evaluation framework was developed in order to evaluate the range of congestion charging scenarios. This incorporated structured decision-making processes and advanced analytics methods. Analysis was carried out using available data from multiple sources, including the 2011 Regional Trip Diary, the 2011 Census, and travel time data from Google Maps API. TransLink's Regional Transportation Model (RTM) was employed as the primary tool used for scenario development and analysis.

Evaluation Framework

Key steps involved in the development of the evaluation framework include understanding the criteria, assessing and narrowing down the list of potential policy tools, development of a comprehensive evaluation framework for more detailed analysis, development and evaluation of congestion charging scenarios, and forming recommendations which resulted from this evaluation process.

A range of indicators and metrics were developed in order to understand, measure, and address the Commission's core objectives around congestion, fairness, and revenue. A qualitative evaluation was then undertaken (MPIC, 2018a) to determine the potential of a range of policy tools. From the full suite of potential policy tools, two were taken forward for further analysis – distance-based charges, and congestion

[1] 54th Annual Meeting of the *Canadian Transportation Research Forum*, May 26 - 29, 2019 at Vancouver, British Columbia

point charges (which could include cordon charges) – from which a number of pricing scenarios were constructed using the Regional Transportation Model. A comprehensive evaluation framework was developed for more detailed analysis and evaluation of the scenarios. Issues and values which the Commission felt were important were covered, including metrics around congestion; fairness; revenue; local effects; ease of implementation; privacy; environment and health; consistency with the Regional Growth Strategy (RGS) and Regional Transportation Strategy (RTS); and future-proofing.

A total of 18 congestion charging scenarios were explored, some of which were examined at multiple charge levels. Two additional scenarios were also developed for benchmarking and comparison purposes – the Baseline 2030 scenario, and the 'pure' marginal social cost (MSC) scenario. The full list and description of these are documented in the Commission's final report (MPIC, 2018b).

The Commission underwent four rounds of iteration and trade-offs using the results of modelling the scenarios, and the evaluation framework. These rounds and scenarios started with basic concepts (e.g. flat distance-based or point charge rates regardless of time of day, location, or direction of travel), and became more complex with each round of iteration. By the end the rates approximated various percentages of the pure MSC scenario.

A number of recommendations were formed following this evaluation process, which consisted of principles and illustrative concepts. The principles were proposed to direct and shape the design of a mobility pricing policy for Metro Vancouver and were developed over the course of the project based on engagement and research findings, as well as Commission discussions. The illustrative concepts reveal how a congestion charge could be applied in the region in a way which meets the principles. These concepts include locations and boundaries of proposed charge points and zones, as well as associated charge rates, which vary by time of day, location, as well as direction of travel for the point charge concepts. Two price structures were proposed for these concepts: one which was set to achieve a minimum level of meaningful congestion reduction – which is described elsewhere in the final report – (set at approximately 50% of the MSC charge rates), and another (set at approximately 75% of the MSC rates) which would achieve more ambitious congestion reduction benefits. Ultimately the charge rates depend on the degree to which the region wishes to reduce congestion, where higher charge rates are required to meet more ambitious targets.

Analytical Approach

The RTM is a four-step transportation demand model, capable of simulating travel behaviour and traffic flow patterns for Metro Vancouver. The model can produce numerous outputs related to travel time, congestion, mode share, vehicle kilometres travelled (VKT), and user costs. The model simulates travel demand patterns across the region according to several factors that are known to influence travel choices (such as the geographical distribution of housing, work, education, services, shopping, and leisure). However, the model is unable to simulate all possible adaptations that people could make to a congestion charge (e.g. changing time of travel). This means that the model's prediction for the amount of change induced by a congestion charging system is a conservative estimate and the estimates for time savings, mode shift, and vehicle distances travelled are best used to compare scenarios to one another. All scenarios were modelled for 2030.

During the course of the project, it became clear that it would be of value to study the effects of a charging scheme on different population groups, for example based on income class. The RTM was not sufficient for such analysis since income is only relevant at a high level, as a zone-specific input parameter. Another data source was required to reach the desired degree of detail. The most recent household Trip Diary survey from 2011 was coupled with the RTM results to enable this exercise. Trips of all sampled household members during a day were recorded. The survey data included fields that were not captured by the RTM, such as income category and trip purpose. The common fields of trip origin, destination, mode, and time of travel were used to join the two datasets. Weights were calculated to fully represent the modelled region.

Travel times, congestion data and charging costs from the RTM were disaggregated to represent each household's complete daily experience.

The household data were used in various parts of the analysis, mostly in relation to fairness metrics. The potential behavioural adaptation that may occur, for example switching to transit or changing destination is not captured in those procedures. The analyses that were based on household data assume that the trip pattern of each household will remain the same. This approach was chosen so as not to underestimate the burden the congestion charging might put on lower income households, which are more likely to adjust their trip patterns. Finally, considering that the data is drawn from a single day, data outliers were excluded from the analysis given the risk of bias during the expansion process to produce annual data.

Application of the theory of marginal social cost (MSC) pricing

While one of the Commission's objectives was to reduce congestion, there was no further direction beyond that – no sense on where, when, or by how much congestion should be reduced. In the absence of a clear congestion reduction target, the project team turned towards the theory of marginal social cost (MSC) pricing (Pigou, 2013) in order to inform the setting of congestion charge rates. The MSC is the key rationale for congestion charging.

Approach to identify MSC charge rates

Identifying and applying the MSC charge rates in the model required an innovative approach to rate-setting within transport demand modelling. Because the RTM is a static model with three time periods and limited heterogeneity in travellers, we adopted the principles of MSC theory, and then approximated the costs. We developed a system optimum assignment to approximate the MSC, where travellers take into account the cost they impose onto others in their route choice. The extra cost is later converted into a charge using an average value of time.

The volume delay functions (VDFs) within the model estimate travel time on a road network link given its free-flow speed, capacity, and vehicle demand. The output is travel time in minutes for each link. The RTM has four principal VDF forms:

- Highway segments;
- Arterials approaching a controlled intersection;
- Arterials with uninterrupted flow; and
- Highway ramp/merge sections

In application, the MSC is essentially the first derivative of the VDF with respect to vehicle demand. In order to apply the MSC in the model, the first step is to create a second set of VDFs. These new VDFs produce the travel time of the original VDF and add the derivative with respect to volume to each trip. This approach charges the MSC in units of time for each road user. The vertical distance between the 'travel time + social cost' curve and 'original VDF travel time' curve is the MSC cost in minutes for a given vehicle demand level (see Figure 1). Note that the original VDF is the estimated travel time on the link. During the model run the original VDF travel time is still calculated to inform transit travel times (which are based on the auto travel time).

For analysis and reporting purposes, the MSC cost in minutes is converted into dollars using weighted average values of time (VOT). However, different users and trip purposes will have different values of time, so for each peak period a weighted average VOT was calculated. The dollar value of the MSC is specifically calculated as:

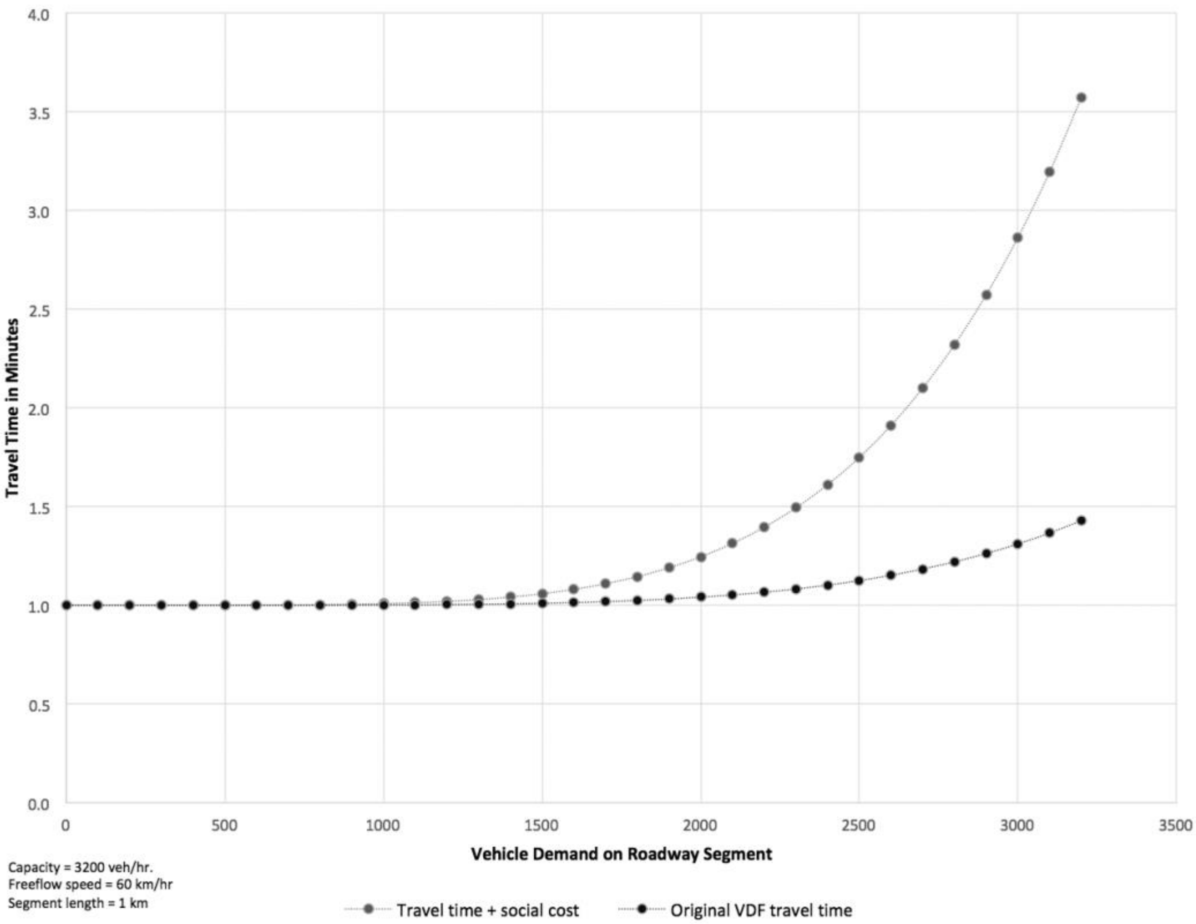
$$c_l(t) = \frac{tt_l^{so}(t) - tt_l^{o}(t)}{60} * VOT(t)$$

Where,

$c_l(t)$ = charge on link l at time t;
$tt_l^{so}(t)$ = system optimal travel time on link l at time t;
$tt_l^{o}(t)$ = user equilibrium travel time on link l at time t;
$VOT(t)$ = average value of time at time t.

In theory the MSC rates set for each link are dynamically priced – the charge is assigned to a specific link and it should move up or down as demand changes in response to prices there and elsewhere. When defining point charge or distance-based scenarios, the MSC model run can be used to identify locations and times where a charge should be applied.

Figure 1 Travel time with original VDF and MSC VDF



Aggregation and approximation of MSC charge rates for scenarios
The initial MSC charge rates that are identified are calculated for each link for three time periods – AM peak, PM peak, and off-peak. However, these raw MSC rates must be aggregated and approximated to fit the point charge or distance-based charge scenarios which have been developed. The MSC model run can be used to identify locations and times where a charge should be applied. However, by aggregating MSC rates into discrete point charges or zones with the same per-kilometre charge rate, significant averaging takes place, which has some implications. First, by averaging congestion on specific links the MSC is no

longer exact – some roads are overpriced, and some are under-priced. Second, since the MSC rates are based on the idea that all surrounding roads also have an optimal charge, the rates are taken somewhat out of context if in a point charge scenario, the surrounding roads are no longer charged. Finally, as people change their behaviour because of charges in a scenario, they may cause new congestion elsewhere, which is not correctly priced because of the aggregation. Ideally, restricted MSC runs would have been conducted to each of the point charge and distance-based scenarios, but using a combined approach of averaging MSC rates over groups of links and using different percentages of the MSC rates allows for appropriate estimation of charges.

For the distance-based charges, the modelled road segments are aggregated into a number of zones, where a range of scenarios are developed for further analysis. To translate the MSC charges to distance-based charge scenarios, a weighted average charge level per km was calculated. This was done uniformly across the region as well as for several geographic zones.

To translate the MSC rates to the congestion point charge scenarios, the bridges in Metro Vancouver around the Burrard Peninsula were grouped based on origin-destination (OD) travel patterns. A total of twelve bridges were placed into five groupings, as well as a further north-south cordon along North Road. For each grouping, a distribution of MSC rates were calculated based on all OD combinations and MSC link-level charges. In addition to time of day, the rates varied between bridges as well as direction of travel. An illustration of the Commission's final scenarios along with the range of charge rates is available in the Commission's final report.

Approach towards addressing fairness

The topic of fairness is considerably more complex relative to congestion and revenue. It is a subjective topic, and there are many aspects to it. Any charging system designed to affect human behaviour will result in different charges across users. A key element of fairness is that these differences are explainable in a consistent and transparent way. The approach used to measure the impacts on fairness was not to define fairness, but rather to establish some underlying pricing principles which relate to fairness, before then evaluating the performance of the scenarios in terms of their alignment with these principles. In addition to these principles, fairness was also addressed by exploring the degree to which low income households were impacted by congestion charging, as well as exploring the amount of money needed to offset any inequities.

Pricing principles

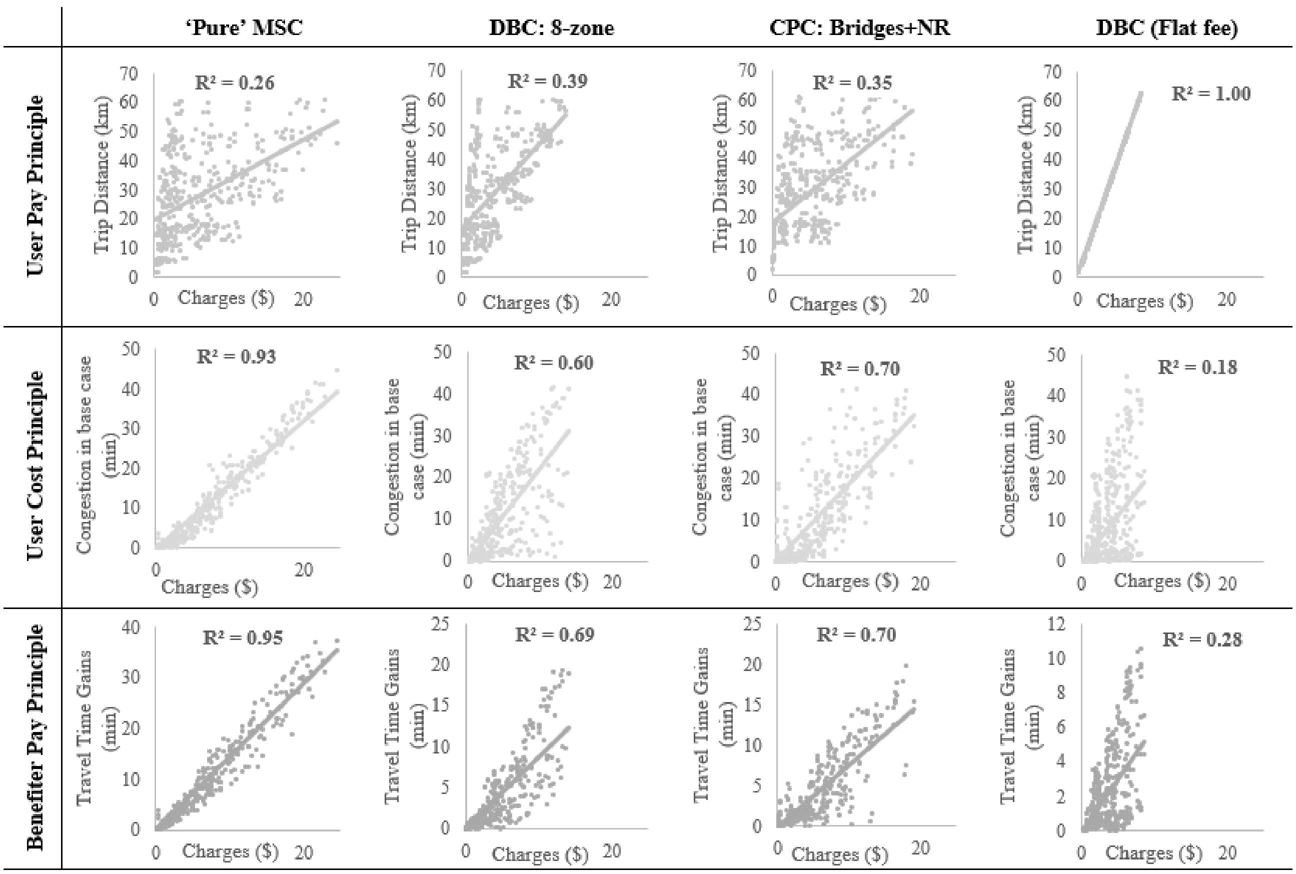
A number of pricing principles have been explored in order to help understand the impacts on fairness. We focus on three of these principles here:

- **User pay principle:** that people should pay in proportion to how much they use the transportation system;
- **User cost principle:** that people should pay in proportion to the amount of congestion they contribute to, in other words the delays they impose on other users;
- **Benefiter pay principle:** that people should pay in proportion to the time savings they experience.

Metrics were developed to assess a scenario's relative alignment with these pricing principles, where scatterplots were produced with either OD trip distance (user pay), congestion of the OD pair in the base case (user cost), and travel time savings per trip (benefiter pay) on the y-axis, and charges per trip on the x-axis. The relationship is tested using a linear regression model where charges for each OD pair served as the dependent variable. The strength of the relationship is tested by calculating the R-squared value (representing the 'goodness of fit') of the trend line. The OD pairs were unweighted and only personal vehicles were included in the dataset. This approach served as a useful exercise to gauge the degree of alignment between principles and scenarios. We share these relationships for four select scenarios here to validate this approach and demonstrate the efficacy of the scenarios. The four chosen scenarios are (i) the ‘pure’ MSC scenario; (ii) an 8-zone distance-based charge (DBC) scenario; (iii) a congestion point charge (CPC) scenario with charges on the bridges and North Road; and (iv) a flat fee DBC scenario.

The MSC scenario is designed to align charges with congestion (user cost principle), and as a result, those who pay more should experience greater travel time savings (benefiter pay principle). The charge rates used for both ‘DBC: 8-zone’ and ‘CPC: Bridges + NR’ are aggregated and approximated from the pure MSC scenario, and then set at a percentage (75%) of the MSC rates. Because of this we expect these scenarios to perform lower than the pure MSC scenario in terms of alignment with both the user cost and benefiter pay principles. Finally, the flat DBC scenario is designed to perform well with regard to the user pay principle, where charges increase with distance driven, regardless of time of day or location driven, or direction of travel. Figure 2 reveals the extent to which these scenarios perform as intended with regard to the three pricing principles.

Figure 2 Performance of select scenarios against pricing principles

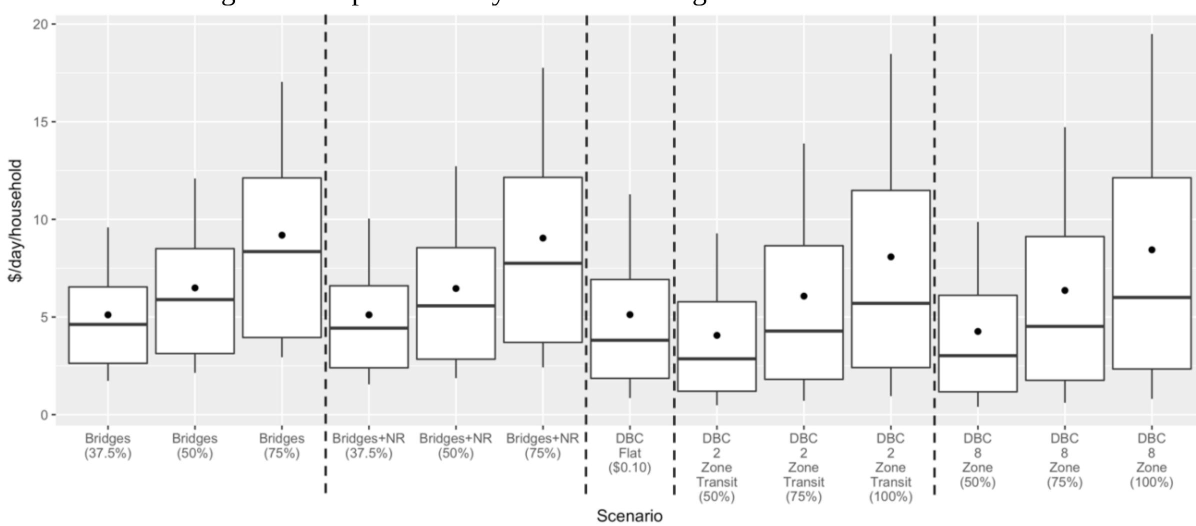


Regarding the user pay principle, the DBC: Flat scenario aligns perfectly, with an R-squared value of 1, and while not surprising, it is helpful to validate the approach used to address the user pay principle. The other three scenarios perform less well in terms of alignment with this principle, with R-squared values ranging between 0.26 and 0.39. This is not surprising given that each of these scenarios were designed to target congestion, with various percentages of the MSC rates being applied. Charges are low at low levels of congestion, and therefore not necessarily correlated well with usage, but rather by times and locations when congestion is ‘bad’. Regarding the user cost principle, given that the pure MSC scenario is designed to target congestion, it is no surprise that the R-squared value for this scenario is so high (0.93). Nonetheless this helps to validate the approach used once more. Given that the DBC 8-zone and CPC Bridges+NR scenarios are approximations of the MSC scenario, once more we expect high R-squared values, but not as high as the pure MSC scenario. This is the case with values of 0.60 and 0.70, respectively. Unsurprisingly, the DBC flat scenario achieves a low R-squared value of 0.18. Finally, regarding the benefiter pays principle, the intention is to explore the relationship between travel time gains and charges paid. As above, the MSC scenario performs the best (R-squared of 0.95), followed by DBC 8-zone and CPC Bridges+NR (0.69 and 0.70, respectively). Finally, the DBC flat scenario obtains a value of 0.28.

Assessing and addressing impacts on low income households

An interesting question related to acceptability and fairness lies in the impact of a congestion charge on households. This is especially important when focusing on lower income households, where the perception of cost is different and they tend to have a narrower range of choice, for example when choosing where to live or work. Household data was used to create descriptive statistics such as the mean and percentiles of household costs on a daily and annual level for the population as a whole and for different subsets, such as income classes or only charged households. It is noted that behavioural responses, for example mode shift or destination choice, are not included in this analysis. In this way, the different adaption patterns between classes do not distort the comparison of costs; everyone is assumed to "stay-and-pay", in other words not change their travel habits. Boxplots of various subsets of the dataset were examined in an effort to make interesting discoveries from the analysis (Figure 3). Typical box-and-whisker plots were produced, for both the absolute charge values and as a proportion of the class average income. Average value and 75th percentiles were chosen to be shown in table form as a representation of a typical and a maximum charge, respectively.

Figure 3 Boxplots of daily household charges for a selection of scenarios



All scenarios revealed lower absolute charges for the low-income classes, yet higher as a percentage of annual income, which is in accordance with research claiming that congestion charging is a regressive policy (Eliasson, 2016). Annual charges were calculated by multiplying the daily charges by 335, a factor used in other parts of the modelling process. The differences in percentage of annual income between the income classes were larger in point-based schemes, however only around 30% of the low-income households would be obliged to pay on a given day. This leads to the median absolute charge of the point-based schemes to be zero for the lowest income class, which is not the case for the distance-based schemes, where every driving household pays something, though less on average.

In the interests of vertical equity, a fair charging system should take into account the financial ability of people to contribute. Although practically it is difficult to differentiate charging according to user income, a compensation can be offered to lower-income households through revenue re-allocation. The height of this compensation varies depending on the nature of the system and the general pricing levels. It is worth analyzing the charging burden on a high-resolution income-differentiated user base.

Knowing the total daily charges imposed on each household, it was possible to divide the dataset by income class. Three income classes were included in the survey, with mean annual incomes of $30,765, $74,910, and $162,055, respectively. For each class, the daily charges can be expanded to annual and expressed as a percentage of the mean annual income by class. The cumulative distributions of these new datasets should be identical in a system directed to equitable contribution among classes.

The method used to determine the height of the compensation that should be allocated to the two lower income classes as a whole can be developed and approximated in the following way:

- The n^{th} quantile of each dataset is found for all n in [a, b]. In this project, we used percentiles and n in [1, 100]. A better approximation can be reached with other values
- The "correction" percentages are calculated, i.e. the differences in charges as a percentage of annual income between the same quantiles of the highest class and each of the other two classes
- The corrections are multiplied by the annual income of the compensated class and the number of households in the quantile, giving the compensation per quantile
- All quantile compensations are summed

Summary and conclusion

This paper has shared part of the approach and methods used to build and evaluate a range of congestion charging scenarios used by the project team that worked with the Mobility Pricing Independent Commission in Metro Vancouver from June 2017 to May 2018. These methods and analyses played a critical role towards guiding and informing the Commission's final recommendations. Innovative methods have been developed to model and approximate the marginal social cost, which was a basis for price-setting of the scenarios. Meanwhile, for fairness, the intention was not to define what is fair and then to measure and evaluate it. Instead we explored the range of ways in which people think of fairness and developed indicators and metrics to account for those things (e.g. pricing principles, costs to low income households, etc.), and then evaluated the performance of scenarios against these metrics. Decisions related to equity and fairness are ultimately informed by value judgements. Therefore, the role is not to decide what is fair, but to present the right information to decision makers who must then decide.

While further research and evaluations continue to explore the distributional impacts of mobility pricing, the evaluation framework and research and analytical methods described in this paper offer an objective, transparent, and transferable approach for other regions and academic institutions who may be interested in researching and evaluating the potential of congestion pricing elsewhere.

References

- Eliasson, J. (2016) Is congestion pricing fair? Consumer and citizen perspectives on equity effects. *Transport Policy*, 52: 1–15.
- MPIC (2018a) Mobility Pricing Independent Commission. *Phase 1 Project Update Full Report.*
- MPIC (2018b) Mobility Pricing Independent Commission. *Metro Vancouver Mobility Pricing Study: Full Report on the Findings and Recommendations for an Effective, Farsighted, and Fair Mobility Pricing Policy.*
- Pigou, A.C. (2013) *The Economics of Welfare.* Palgrave Macmillan, U.K.