

Selecting Optimal Tolling Levels: A Case Study for the Fraser River in the Greater Vancouver Area ^{*}

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Abstract

The recent addition of a toll on the Port Mann Bridge in Greater Vancouver has resulted in an observed increase in traffic volumes on alternate routes crossing the Fraser River. The result has been lower than expected volumes on the Port Mann Bridge and increased congestion on other major arteries in the region. This paper describes the development of a mathematical programming model to determine an optimal tolling system for the four main Fraser River crossings in the Greater Vancouver area: the Port Mann Bridge, the Alex Fraser Bridge, the Pattullo Bridge, and the Massey Tunnel. Two scenarios are discussed, starting with the current situation of one toll on the Port Mann Bridge, while the second will open the possibility of implementing a toll on all four crossings. The intention is to minimize congestion in the region through the redistribution of traffic.

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1 Introduction

Recently, the Port Mann Bridge linking Surrey and Coquitlam in Greater Vancouver was replaced as part of the Port Mann/Highway 1 Improvement Project (PMH1 Project), due to aging infrastructure and the desire to decrease congestion along the Trans-Canada Highway. The new Port Mann Bridge was opened on September 18, 2012 and is equipped with a total of ten lanes, twice as many as the previous bridge. In order to recover the costs of the project without drawing on financial resources directed at other provincial sectors, the British Columbia Ministry of Transportation mandated a toll on the new bridge. Recent observed increased traffic volumes on alternate routes crossing the Fraser River suggest that the toll has led a portion of the affected population to avoid the bridge [1]. The result has been increased congestion on other major arteries in the region and lower than expected volumes on the Port Mann Bridge. The goal of this paper is to establish an optimal tolling system for the Fraser River crossings in the Greater Vancouver area through the development of a model using mathematical programming. The intention is to minimize congestion in the region through the redistribution of traffic and to make effective use of the additional capacity on the Port Mann Bridge.

The section of the Trans-Canada Highway that includes the Port Mann Bridge is considered by the Province of British Columbia as the “busiest and most economically critical route in Greater Vancouver” [2]. For this reason, the Province has invested heavily in the PMH1 Project and they intend to recover the \$3.3 billion cost of the project by 2050 through the toll on the Port Mann Bridge [3]. On December 7, 2012, three months following the bridge’s opening, an introductory toll of \$1.50 for passenger vehicles was implemented on the crossing. The current full tolling structure came into effect on January 1, 2014 with an increase to \$3.00 for passenger vehicles. Due to the limited precedent of tolls on major arteries in the Greater Vancouver area, the implementation of a toll on the Port Mann Bridge has been a sensitive issue for a large portion of the general population. Regional cities and residents have asked for a change to the system due to the perceived effects of congestion on alternate routes since the toll on the Port Mann Bridge [4].

The model outlined in this paper will show that the current situation of only having a toll on the Port Mann Bridge is insufficient to meet revenue requirements. This is a result of the decrease in traffic volume on this bridge due to the toll’s implementation. With an objective of minimizing congestion, the model shows that a toll on all crossings under consideration across the Fraser River is ideal in order to meet all requirements. This multi-toll scenario attempts to demonstrate how tolls shift traffic between crossings and assumes that commuters take toll price into consideration when choosing their route - that is, an increase in the toll on a crossing comparative to others will divert a certain percentage of traffic onto alternate crossings. The resulting tolling system obtained includes a toll on all crossings under consideration, with an average toll price lower than the current price on the Port Mann Bridge.

1.1 Scope of Project

This paper considered the four following major crossings on the Fraser River in the Greater Vancouver area: the Port Mann Bridge, the Pattullo Bridge, the Alex Fraser Bridge, and the Massey Tunnel (see Figure 1). The Queensborough Bridge, the Oak Street Bridge, and the Knight Street Bridge are not individually considered alternate routes to the Port Mann Bridge and do not cross the main channel of the Fraser River. Therefore, they will not belong to the scope of this project. Due to its geographical disconnect, this paper will not view the Golden Ears Bridge as an alternative to the others mentioned. As such, the authorities responsible for operating and maintaining the Fraser River crossings under consideration are Translink, the Transportation Investment Corporation (TI Corp), and the Province of British Columbia through the Ministry of Transportation.

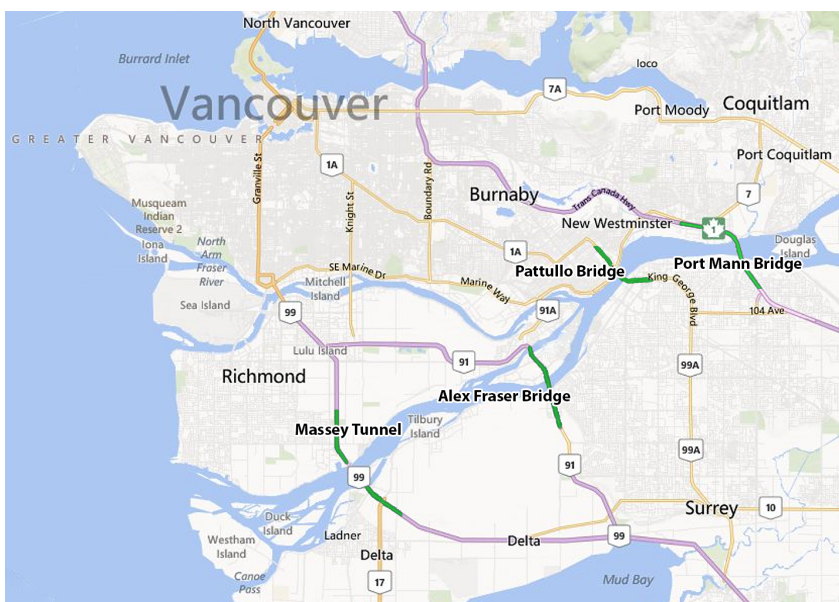


Figure 1: Major crossings on the Fraser River in the Greater Vancouver area [5]

2 Preliminaries

2.1 Data Collection

Traffic volume data was collected from Translink, the BC Ministry of Transportation, and TI Corp. The scope of the data obtained covers hourly, daily, and annual average daily traffic volumes for the four crossings [6] [7] [8] [9] [10] [11] [12] [13] [14] [15] [16] [17] [18]. Some of the data is also divided by traffic direction. The time frame taken into consideration for hourly and

daily data is from January 1, 2008 to January 31, 2014. The range of the annual average traffic data extends from 2004 to 2013. The data obtained from these sources will be considered as accurate. This is supported by the availability of hourly traffic as well as breakdowns of the volume by specific vehicle class. This assumption will simplify the model by preventing the need for probabilistic methods to deal with estimates and confidence intervals.

Despite the extent of the data collected, there are areas where data is missing, including months that were not reported by the respective authorities. For instance, there is a gap in daily traffic volume data for the Pattullo Bridge from January 1, 2008 to October 1, 2012, while information pertaining to the Port Mann Bridge after April 2012 is limited only to daily values for January 2013 and 2014. An attempt was made to confirm the unavailability of any substantial missing data. Any time frames lacking reported data have been supplemented through the use of government reports, newspaper articles, or statistical analysis.

While data on transit ridership volumes over the Fraser River was also desired, no data of any significant relevance to passenger crossings by SkyTrain or bus was available. For example, recent SkyTrain ridership data is not currently available by route travelled and any increase in passenger crossings of the Fraser River is unobservable. It is therefore assumed that this transit ridership is unquantifiable and that any shift to transit due to tolling on the Port Mann Bridge is simply reflected in the change in observed traffic volumes.

2.2 Defining AADT: Traffic Volume Measurement

Average annual daily traffic (AADT) is a standard term used in transportation planning to measure observed traffic volumes. In this paper, AADT is defined as the annual daily average of weekday, non-holiday traffic. Weekend traffic volumes are generally lower and less predictable than those experienced during the week. Variability in the data is therefore significantly reduced by only looking at weekday traffic. Weekend or holiday traffic may experience high congestion but since a broader, less consistent hourly distribution of traffic occurs, these days are not included in defining AADT. The discrepancy between AADT and weekend traffic volumes will however be taken into account when projecting tolling income to prevent overestimating revenue generation. AADT is easily derived from the obtained data of daily traffic values or is provided on the generated reports.

2.3 Defining Congestion: LOS Standards

With the goal of developing a model to minimize congestion in the region, a means of quantifying congestion was required. Over the past 50 years, the Transportation Research Board (TRB) has gathered data for various methods of transportation across roadways in the United States. Their findings and relationships have been compiled in the Highway Capacity Manual (HCM). This manual provides a standardized approach of calculating a road's Level of Service (LOS), which is defined as a "quality measure describing operational conditions within a traffic stream, generally

in terms of such service measures as speed and travel time, freedom to maneuver, traffic interruptions, and comfort and convenience” [19].

The HCM defines six LOS thresholds for one-directional traffic volume from free-flowing A to over capacity F. This allows for the level of congestion experienced to be measured based on the number of vehicles observed per hour in one direction on the road. These levels are calculated based on a number of road characteristics. For simplicity, the LOS calculations used will only consider the number of lanes and Free Flow Speed (FFS). Adjustments for access point density, passenger car equivalents, and median type are not included due to the added complexity of relationships that would occur [20]. Table 1 shows the calculated LOS thresholds for each crossing. When the volume observed on a road surpasses each threshold, a new congestion level is reached. From the HCM, only LOS A to E can be quantified with volume capacities since LOS F represents a level of traffic greater than the capacity of the road.

Crossing	Number of lanes	FFS km/hr	LOS A	LOS B	LOS C	LOS D	LOS E
Port Mann	4	100	2640	4320	6200	7920	8800
Pattullo	2	40	646	1080	1582	2258	3200
Alex Fraser	3	90	1800	2970	4290	5550	6300
Massey	2*	80	1100	1800	2600	3420	4000

Table 1: Upper bound on Levels of Service (LOS) standards and Free Flow Speed (FFS) limits

*Note: During some hours the Massey Tunnel is calculated for 1 lane/3 lanes

A lane width adjustment is included for the Pattullo Bridge due to significant difference between its lane width of 2.9m and the current standard of 3.6m [21] [22]. Based on HCM recommendations, FFS has therefore been reduced by 10 km/hr from the posted speed limit to take this into account. The other three crossings under consideration have sufficient lane widths allowing the FFS to equal the posted speed limit of the roadway. The LOS thresholds for the four-lane Massey Tunnel also change during the six hours each weekday in which the counter-flow lane is in effect. This switches the tunnel to three lanes in the high volume direction and one lane in the low volume direction. For example, the LOS A threshold increases to 1,650 vehicles for a direction using three lanes and decreases to 550 for one lane.

While the HCM contains information for both highways and freeways, all of the Fraser River crossings will be considered and evaluated as highways. The Port Mann Bridge could be considered by the HCM as a freeway due to the roadway being divided at all times and its lack of traffic signals. However, due to the close proximity of merge and exit lanes on either side of the bridge, considering the Port Mann Bridge as a highway is appropriate. In making this assumption, the resulting LOS values are more conservative and ensure that the model does not overestimate the capacity of the bridge.

3 Methodology

The following section describes and motivates the non-linear mathematical programming model. The model developed will determine a tolling system and project the AADT volume on each crossing that satisfies the constraints associated with the problem such that congestion is minimized in the region.

3.1 Revenue Requirements

When the toll was implemented on the Port Mann Bridge, the Province of British Columbia stipulated that the \$3.3 billion cost of the PMH1 Project needed to be recovered through toll revenue by 2050. Maintaining this revenue level is the first key requirement. Required daily revenue was based on the expected income of \$120 million for the first year of tolling, which equates to an average annual daily revenue of \$330,000 [23]. The model will assume that revenue requirements in later years will have a stronger probability of being met if the first year requirement is also met. Historical data shows that average weekend traffic is approximately 88% of AADT. Therefore, a factor of 96.6% will be incorporated when calculating average daily revenue.

$$\frac{5 \text{ weekdays} + 0.88 * 2 \text{ weekend days}}{7 \text{ days}}$$

3.2 Base Year

In order to take user preference into consideration and to make congestion comparisons, 2012 was set as a base year for the distribution of traffic volumes between the four crossings. This was the last year prior to the implementation of a toll on the Port Mann Bridge and can be considered as a user equilibrium for the network. AADT values were directly available on obtained reports or derived from daily traffic volumes. For the Port Mann Bridge, AADT information for the entire year is only available until 2011. In this case, a regression analysis was used to estimate the AADT in 2012 based off of the observed AADT on the bridge between 2004-2011. These values are presented in Table 2. Although the introductory toll on the Port Mann Bridge was introduced in December 2012, it is assumed that this did not significantly affect the AADT for the year. The base year is taken into consideration by setting a range for the projected AADT values in the model. A lower bound will be set by α and an upper bound will be set by β , each being percentage bounds of the base year.

Port Mann	Pattullo	Alex Fraser	Massey
108887*	69900	115250	85516

Table 2: 2012 AADT base year
 *Note: estimated

Sources: Ministry of Transportation reports for the Alex Fraser Bridge and Massey Tunnel [6] [7], New Westminster City Council for the Pattullo Bridge [24]

3.3 Predicted Traffic for 2014

In order to estimate the distribution of traffic and the resulting congestion expected in 2014 given the current tolling situation, an estimate was derived for the 2014 AADT on the four crossings of interest. These estimates are shown in Table 3. For the Port Mann Bridge and the Pattullo Bridge, available data includes the AADT for January 2014. An analysis of historical data indicated that on average, the weekday traffic volume experienced on both crossings in January is consistently 97% of the yearly AADT. This relationship was assumed to be a valid for 2014 and the overall AADT was projected based on the observed volume in January 2014. For example, the average weekday traffic volume in January 2014 on the Port Mann Bridge was observed to be 95,147 vehicles, resulting in a projected 2014 AADT on the bridge of 98,090. The most recent data was used to project the total AADT in 2014 in order to take into account the latest shifts in traffic as a result of the increased toll on the Port Mann Bridge as of January 1, 2014.

This projection method however was not possible for the Alex Fraser Bridge and the Massey Tunnel as no January 2014 data was available. Instead, a time-series linear regression was performed on AADT data for the Alex Fraser Bridge from 2007-2013 and from 2010-2013 for the Massey Tunnel. Prior to 2010, the AADT observed on the Massey Tunnel was variable and did not exhibit a noticeable trend. A constant decline is evident however in the last three years and a prediction on these three years provides a statistically significant result.

Port Mann	Pattullo	Alex Fraser	Massey
98090	81795	117872	82329

Table 3: 2014 AADT estimates

These crossing projections also provide an estimate of the total AADT expected across the Fraser River in 2014 and serves as a lower bound for the overall traffic volume to be allocated in the model. The total expected AADT to cross the Fraser River in 2014 is estimated to be 380,086. For simplification purposes and due to prediction error, 380,000 will be considered as the total predicted AADT for 2014 moving forward.

3.4 Hourly Distribution

Using hourly traffic volumes in each direction sampled from four different months, an hourly distribution of traffic was established separately for each crossing (see Appendix C). The four months selected were spaced evenly to adjust for seasonality. Only non-holiday, weekday traffic was used in order to stay consistent with the AADT values. The total traffic each hour across the sampled months was used to calculate the percentage of total daily traffic volume observed during the hour and in each direction. This provides an hourly distribution for the north and south directions on each crossing for an average weekday. These percentages are used as parameters

in the model so that traffic volumes, and the resulting LOS experienced, can be analyzed on an hourly basis. Given a projected AADT for a crossing, the expected number of vehicles observed in a given hour and direction can be estimated. Figure 2 shows the resulting hourly distribution by direction for the Pattullo Bridge.

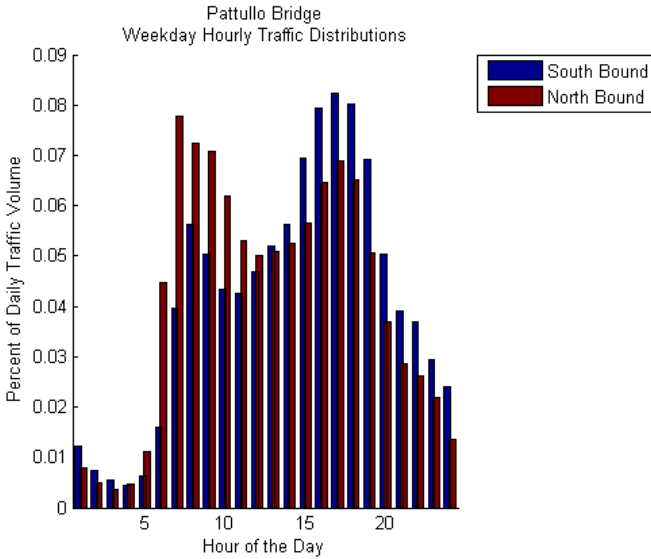


Figure 2: Pattullo Bridge weekday hourly traffic distribution [18]

3.5 Congestion Weights

For each LOS threshold, a corresponding weight was applied to represent the congestion level experienced. As congestion on a crossing increases, higher LOS thresholds are reached which corresponds to a higher congestion weight.

The weights assigned to the different LOS thresholds are as such: 1 for LOS A, B and C, 2 for LOS D, 4 for LOS E, and 7 for LOS F. The weights used are consistent across all crossings as necessary distinctions are already taken into account in the LOS calculation. Given the values determined for LOS thresholds for each bridge and these corresponding weights, a convex and monotonic piecewise linear function was developed for the five defined LOS, with each consecutive pair of weights and LOS thresholds linked in a linear fashion. Figure 3 shows the resulting function for the Alex Fraser Bridge. Since the linear approximation assigns a more precise weight, this is preferred over using a discrete value function that assigns one weight to all traffic volumes between two given LOS thresholds. The function $C_{ijk}(X_i)$ provides the corresponding hourly

congestion weight given traffic volume X_i for each crossing i , direction j , and hour k :

$$C_{ijk}(X_i) = \begin{cases} w_{iA} & \text{if } (X_i p_{ijk}) \leq L_{iA} \\ w_{iA} + (w_{iB} - w_{iA}) \left(\frac{(X_i p_{ijk}) - L_{iA}}{L_{iB} - L_{iA}} \right) & \text{if } L_{iA} < (X_i p_{ijk}) \leq L_{iB} \\ w_{iB} + (w_{iC} - w_{iB}) \left(\frac{(X_i p_{ijk}) - L_{iB}}{L_{iC} - L_{iB}} \right) & \text{if } L_{iB} < (X_i p_{ijk}) \leq L_{iC} \\ w_{iC} + (w_{iD} - w_{iC}) \left(\frac{(X_i p_{ijk}) - L_{iC}}{L_{iD} - L_{iC}} \right) & \text{if } L_{iC} < (X_i p_{ijk}) \leq L_{iD} \\ w_{iD} + (w_{iE} - w_{iD}) \left(\frac{(X_i p_{ijk}) - L_{iD}}{L_{iE} - L_{iD}} \right) & \text{if } L_{iD} < (X_i p_{ijk}) \leq L_{iE} \\ w_{iE} & \text{if } L_{iE} < (X_i p_{ijk}) \end{cases}$$

To measure the cost of congestion on a crossing, a congestion factor for each hour is calculated by multiplying the expected hourly traffic volume with the associated congestion weight. Doing so normalizes the level of congestion by the number of vehicles that experience it. The sum of all hourly congestion factors for both directions represents a crossing's congestion factor, that is, the normalized cost of congestion experienced. The sum of congestion factors for all crossings can be used as a means of quantifying the amount of congestion experienced in the region.

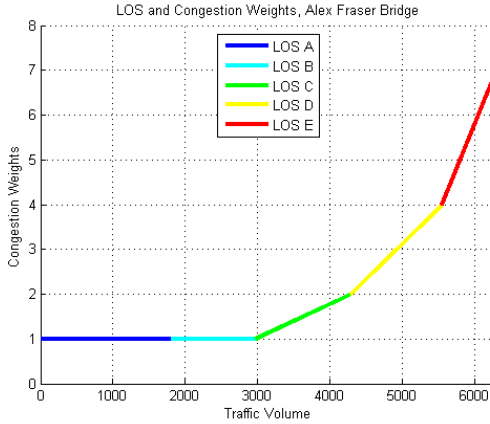


Figure 3: Congestion weights based on the LOS traffic volumes for the Alex Fraser Bridge

3.6 Expected AADT Given Toll Price

To obtain a relationship between toll price and projected AADT, traffic volume changes on the Port Mann Bridge were analyzed. Specifically, the average weekday traffic observed in January 2012, 2013, and 2014 was compared due to data availability and to control for seasonality (see Table 4). These time frames represent the volume prior to the toll, the period during the introductory \$1.50 toll, and the period with the \$3.00 toll. Between January 2012 and 2013, the average

weekday traffic on the Port Mann Bridge decreased by 4.59% and between January 2013 and 2014, it decreased a further 3.04%. An exponential function was constructed to model this declining relationship for AADT volumes based on the observed percentage change in traffic with respect to the toll price. The base year AADT values were used as the expected traffic volume with no toll. An exponential function was chosen based on the rationale that traffic volume change is steepest when a toll is initially introduced and subsequent toll increases have a lesser effect on volume change. The resulting relationship for the Port Mann Bridge is as follows, where t is its toll price:

$$\text{Expected traffic volume} = 108887e^{-0.03t}$$

Similar exponential functions for the three other crossings were also developed based on extrapolating the observed relationship between toll price and percent change in traffic volume on the Port Mann Bridge. This was based on the assumption that the behaviour of traffic - that is, the change in traffic volume given a change in the toll price - will be consistent over the region.

	January 2012	January 2013	January 2014
Average			
Weekday Traffic	102856	98131	95147
Percent change			
from previous year		-4.95%	-3.04%

Table 4: January 2012, 2013, 2014 Port Mann Bridge traffic volume and percentage change

Sources: 2012 from Ministry of Transport daily report [8],
2013, 2014 from TI Corp report [25]

In order to model the existing scenario of only one toll on the Port Mann Bridge, the exponential function models how the expected AADT will change with respect to the toll price. It is also important to know how the traffic that leaves the Port Mann Bridge as a result of the toll will disperse. Based on the observed traffic volume increases on the Pattullo Bridge and the Alex Fraser Bridge since the implementation of each toll, twice as many users chose the Pattullo Bridge as their alternate route over the Alex Fraser Bridge. It is therefore assumed that two-thirds of the traffic that leaves the Port Mann Bridge as a result of the toll will move to the Pattullo Bridge while the other one-third will shift to the Alex Fraser Bridge. The traffic rerouting to the Massey Tunnel was unobservable and thus considered to be minimal. As such, no traffic is directly modeled to move to that crossing.

However, a cooperative relationship on how traffic would redistribute between crossings in relation to all toll prices is required in considering a multi-toll scenario, whereby there is the possibility of implementing a toll on any crossing. In this case, a net toll was created in order to balance the interaction between multiple tolls. This was introduced to calculate whether, in relation to

other tolls in the region, a given toll price on a crossing would have a net gain or net loss of traffic. The net toll calculations (for each crossing i) are as follows:

$$N_i(t_1, t_2, t_3, t_4) = \begin{cases} t_1 - \left(\frac{2}{3}t_2 + \frac{1}{3}t_3\right) & \text{if } i = 1, & \text{Port Mann Bridge} \\ t_2 - \left(\frac{1}{2}t_1 + \frac{1}{2}t_3\right) & \text{if } i = 2, & \text{Pattullo Bridge} \\ t_3 - \left(\frac{1}{4}t_1 + \frac{1}{2}t_2 + \frac{1}{4}t_4\right) & \text{if } i = 3, & \text{Alex Fraser Bridge} \\ t_4 - t_3 & \text{if } i = 4, & \text{Massey Tunnel} \end{cases}$$

$N_i(t_1, t_2, t_3, t_4)$ will hereafter be referenced to as N_i

The net toll calculation is different for each crossing based on the relationships observed with the introduction of tolls on the Port Mann Bridge. As per the relationship suggested above, the net toll on the Port Mann Bridge is comprised of two-thirds of the toll on the Pattullo Bridge and one-third of the toll on the Alex Fraser Bridge. From this observed relationship, the following assumptions are made: diverted traffic from the Pattullo Bridge utilizes the Port Mann Bridge and the Alex Fraser Bridge, diverted traffic from the Alex Fraser Bridge utilizes all other crossings with an assumed double weight on the Pattullo Bridge, and diverted traffic from the Massey Tunnel is assumed to utilize only the Alex Fraser Bridge. These assumptions may be seen as restrictive however the model will react to increased congestion felt by any change to the net tolls.

The expected volume given toll functions are a two part piecewise function dealing with positive and negative net tolls. A positive net toll is simply the exponential relationship generated above based on the traffic decline observed on Port Mann Bridge. A negative net toll would imply a commuter attraction to using a crossing based on higher toll prices on neighbouring crossings. The traffic added to a crossing given a negative net toll is found from the loss of the traffic from the higher tolled neighbouring crossings with respect to the base year. The expected AADT given net toll calculations are as follows:

$$M_1(N_1, N_2, N_3) = \begin{cases} Y_1 e^{-0.03N_1} & \text{if } N_1 \geq 0 \\ Y_1 + (1 - e^{-0.03N_1}) \frac{2N_2 Y_2 + N_3 Y_3}{2N_2 + N_3} & \text{if } N_1 < 0 \end{cases}$$

$$M_2(N_1, N_2, N_3) = \begin{cases} Y_2 e^{-0.03N_2} & \text{if } N_2 \geq 0 \\ Y_2 + (1 - e^{-0.03N_2}) \frac{N_1 Y_1 + N_3 Y_3}{N_1 + N_3} & \text{if } N_2 < 0 \end{cases}$$

$$M_3(N_1, N_2, N_3, N_4) = \begin{cases} Y_3 e^{-0.03N_3} & \text{if } N_3 \geq 0 \\ Y_3 + (1 - e^{-0.03N_3}) \frac{N_1 Y_1 + 2N_2 Y_2 + N_4 Y_4}{N_1 + 2N_2 + N_4} & \text{if } N_3 < 0 \end{cases}$$

$$M_4(N_3, N_4) = \begin{cases} Y_4 e^{-0.03N_4} & \text{if } N_4 \geq 0 \\ Y_4 + Y_3(1 - e^{-0.03N_4}) & \text{if } N_4 < 0 \end{cases}$$

$M_i(N_1, N_2, N_3, N_4)$ refer to the Port Mann Bridge, Pattullo Bridge, Alex Fraser Bridge, and Massey Tunnel respectively ($i \in \{1, 2, 3, 4\}$), and will hereafter be referred to as M_i .

3.7 Assumptions

The following is a summary of key assumptions applicable to the model:

- Data obtained from the given reports will be considered as accurate.
- All roads are considered as highways as defined by the HCM manual.
- The relationship between traffic volume and toll price on all crossings is the same as the relationship observed on the Port Mann Bridge, in percent.
- All traffic over a tolled crossing is subject to the toll.
- Implementing tolls on multiple crossings in the region may reduce total traffic volume, however due to the unknown magnitude, this reduction will not be considered.
- If the first year revenue requirements are met, then all subsequent years will be met as well.
- The tolls implemented in December 2012 had little effect on annual AADT values for 2012.

3.8 Factors Not Included

The following is a summary of elements that will be considered out of scope:

- Transit ridership changes as a result of the toll on the Port Mann Bridge are unavailable over the Fraser River and will not be considered.
- Due to its geographical disconnect, this paper will not treat the Golden Ears Bridge as an alternative to the others considered.
- The Queensborough Bridge, the Oak Street Bridge and the Knight Street Bridge are not considered due to the fact that these bridges are not individually alternate routes to the Port Mann Bridge and do not cross the main channel of the Fraser River.
- Data currently available does not allow for an analysis of time-of-day toll pricing. Only fixed toll prices will be explored.

4 First Scenario: One Toll on the Port Mann Bridge

The goal of the first scenario is to minimize congestion in the entire region and determine the optimal toll price for the Port Mann Bridge. This initial model does not introduce any new tolls on the other crossings but adjusts the existing toll in order to better distribute traffic among the crossings. The full details of this model are in Appendix B.1.

4.1 Decision Variables

Having obtained and analyzed all relevant data, two sets of decision variables were identified. These variables are set in order to optimize the tolling system. The first set represents the projected AADT on three of the crossings while the second set represents the assigned toll on the Port Mann Bridge. There is no decision variable for the Port Mann Bridge AADT since the toll price on the bridge sets the expected traffic volume in the model.

$$\begin{aligned} X_i &= \text{projected AADT on the } i^{\text{th}} \text{ crossing where } i \in \{2, 3, 4\} \\ t_i &= \text{the toll price where } i \in \{1\} \end{aligned}$$

4.2 Auxiliary Variables

A set of auxiliary variables were incorporated to account for the projected AADT as well as redistribution of traffic from the Port Mann Bridge given the implementation of the toll.

$$\begin{aligned} Y_1 e^{-0.03t_1} &= X'_1 \\ X_2 + \frac{2}{3}(Y_1 - X'_1) &= X'_2 \\ X_3 + \frac{1}{3}(Y_1 - X'_1) &= X'_3 \\ X_4 &= X'_4 \end{aligned}$$

4.3 Objective Function

The objective is to disperse traffic volume and therefore minimize congestion throughout the region. The hourly traffic distributions were applied to the auxiliary AADT in order to find the approximate traffic volume experienced during each hour. These were then weighted by the appropriate congestion weights. These congestion costs were calculated for all hours of the day in both directions and were summed to find the total congestion factor on that crossing. The aim of the objective function is to minimize the total congestion among all crossings.

The following indices are used:

$$\begin{aligned} i &= 1, \dots, 4 \text{ for the crossings: Port Mann, Pattullo, Alex Fraser, Massey} \\ j &= 1, \dots, 2 \text{ for the directions: North, South} \\ k &= 1, \dots, 24 \text{ for the hours of the day} \\ n &= A, \dots, E \text{ for the Levels of Service} \end{aligned}$$

$$\text{Objective Function} = \min \sum_{i=1}^4 \sum_{j=1}^2 \sum_{k=1}^{24} C_{ijk}(X'_i) X'_i p_{ijk}$$

Given a traffic volume X_i , $C'_{ijk}(X_i)$ is the congestion weight assigned to the i^{th} crossing in the j^{th} direction during the k^{th} hour, and is defined as previous.

4.4 Parameters

- p_{ijk} = Percentage of the i^{th} crossing's AADT in the j^{th} direction during the k^{th} hour
 Y_i = AADT on the i^{th} crossing from the base year 2012
 L_{in} = LOS threshold upper bound on the i^{th} crossing for the n^{th} level
 w_{in} = Congestion weighting on the i^{th} crossing for the n^{th} Level of Service
 D = Required average annual daily revenue for the tolling system (\$330,000)
 V = Total predicted AADT volume for 2014 (380,000)
 α = Margin of difference for lower bounds of AADT for the base year 2012 (0.08)
 β = Margin of difference for upper bounds of AADT for the base year 2012 (0.5)

4.5 Constraints

1. The total amount of traffic in the system must remain above the predicted traffic volume for 2014.

$$\sum_{i=1}^4 X'_i \geq V$$

2. The revenue generated from the tolling system must meet or exceed what is required by the BC Provincial Government (\$330,000) in order to recover the entire cost of the PHM1 Project, normalized for weekends.

$$0.966(t_1 X'_1) \geq D$$

3. For each crossing, the projected AADT volume should remain above a $(1 - \alpha)$ % of the base year. An α of 0.08 will be used in this model.

$$X_i \geq Y_i(1 - \alpha) \quad i = 2, 3, 4$$

4. For each crossing, the projected AADT volume should also remain below a $(1 + \beta)$ % of the base year. A β of 0.5 will be used in this model.

$$X_i \leq Y_i(1 + \beta) \quad i = 2, 3, 4$$

4.6 Results

The results from this first scenario show that the optimal tolling price on the Port Mann Bridge, in order to meet all requirements, is \$3.48. This is shown in Table 5. The resulting toll for this first scenario is greater than that currently applied to the Port Mann Bridge. Therefore with the given toll, it can be predicted that the current revenue generation will fall short of the desired amount of \$120 million in the first year of operation [23]. The maximum congestion weights show that there are two crossings, the Pattullo Bridge and the Alex Fraser Bridge, that will be operating at LOS E, during the peak hours of the day. At this level there is not much ability on both bridges

for the traffic flow to absorb any disruptions. As such, a new tolling system is justified, to redistribute traffic in a way that would see a reduced congestion on these two crossings.

Crossing	Port Mann	Pattullo	Alex Fraser	Massey
AADT	98081	71440	121772	88707
Max Congestion Value	1.00	6.11	4.46	3.87
Max LOS	B	E	E	D
Toll (\$)	3.48			
Revenue/Day (\$)	330,000		Total Congestion 788629	

Table 5: Results of the one toll scenario

5 Multi-Toll Scenario: New Tolling System for Four Crossings

The goal of this multi-toll scenario is to minimize congestion in the region and determine an optimal tolling system for the four crossings of interest. This second scenario allows for the possibility of a toll on the Pattullo Bridge, the Alex Fraser Bridge, and the Massey Tunnel in addition to the Port Mann Bridge in an attempt to distribute traffic among the crossings and lower overall congestion. The full details of this model are in Appendix B.2.

5.1 Decision Variables

More decision variables were introduced for this second model. The first set represents the projected AADT on each of the four crossings while the second set represents their assigned tolls.

$$\begin{aligned}
 X_i &= \text{projected AADT on the } i^{th} \text{ crossing where } i \in \{1, 2, 3, 4\} \\
 t_i &= \text{the toll price where } i \in \{1, 2, 3, 4\}
 \end{aligned}$$

5.2 Objective Function

The aim of the objective function remains to minimize the total congestion among all crossings. In this case, the hourly traffic distributions were applied to the projected AADT and weighted by the appropriate congestion weights.

$$\text{New Objective Function} = \min \sum_{i=1}^4 \sum_{j=1}^2 \sum_{k=1}^{24} C_{ijk}(X_i) X_i p_{ijk}$$

Given traffic volume X_i , $C_{ijk}(X_i)$ is the congestion weight assigned to the i^{th} crossing in the j^{th} direction during the k^{th} hour, and is defined as previous.

5.3 Additional Parameter

R = Maximum daily revenue for the tolling system (\$600,000)

5.4 Constraints

1. The four projected AADT should be no more than the expected traffic volume given the net toll found by M_i .

$$X_i \leq M_i$$

2. The total amount of traffic in the system must remain above the predicted traffic volume for 2014.

$$\sum_{i=1}^4 X_i \geq V$$

3. The revenue generated from the tolling system must meet or exceed what is required by the BC Provincial Government (\$330,000) in order to recover the entire cost of the PHM1 Project, normalized for weekends.

$$0.966 \sum_{i=1}^4 (X_i t_i) \geq D$$

4. The revenue generated from the tolling system has an upper bound to prevent the model attaining cost prohibitive tolls beyond the reliability of the data. A maximum revenue of \$600,000/day or \$219 million/year, roughly twice the required amount, was set.

$$0.966 \sum_{i=1}^4 (X_i t_i) \leq R$$

5. For each crossing, the projected AADT volume should remain above a $(1 - \alpha)$ % of the base year. An α of 0.08 will be used in this model.

$$X_i \geq Y_i(1 - \alpha)$$

6. For each crossing, the projected AADT volume should also remain below a $(1 + \beta)$ % of the base year. A β of 0.5 will be used in this model.

$$X_i \leq Y_i(1 + \beta)$$

5.5 Results

Table 6 shows the results of the optimal multi-toll system. The solution has assigned a toll to all four crossings. A reduction in the average toll price paid and the total congestion factor compared to the one-toll scenario is noticed. With this change, there is a significant increase in revenue. The maximum LOS reached is now one level lower on the Alex Fraser Bridge compared with the one-toll scenario. This signals that there would be a more efficient transfer of vehicles

moving across the Fraser River. In solving this multi-toll scenario, the upper bound on the volume given the toll on each bridge is met. This seems intuitive in preventing slack in the model, that is, charging a higher toll on a crossing than is necessary.

Crossing		Port Mann	Pattullo	Alex Fraser	Massey
Predicted 2014	AAADT	98090	81795	117872	82329
	Max Congestion value	1.00	7.00	3.89	3.28
	Max LOS	B	F	D	D
Multi Toll Solution	AAADT	110443	69965	113625	85967
	Max Congestion value	1.03	5.91	3.58	3.62
	Max LOS	C	E	D	D
	Toll (\$)	1.23	1.58	1.93	1.80
	Net Toll (\$)	-0.47	0.00	0.47	-0.13
Revenue/Day (\$)		600,000		Total Congestion	740162

Table 6: 2014 AADT estimates compared to multi-toll scenario results

When the comparison is made between this multi-toll scenario, the one toll scenario, and the predicted 2014 volumes, the total congestion factor experienced in the multi-toll scenario is the lowest. Based on the 2014 predicted volume, the Pattullo Bridge would experience a maximum congestion weight of 7, implying a LOS F. By definition of this LOS, it can be inferred that the bridge capacity cannot handle the traffic volume. As seen in Table 6, the multi-toll scenario reaches a maximum congestion weight of 5.91 for the Pattullo Bridge, inferring a LOS E during peak hours of the day. At this level, the bridge is able to handle the traffic volume. Additionally, it is observed that the Port Mann Bridge will be operating at a maximum of LOS C in the multi-toll solution, one level greater than both the one toll scenario and projected 2014 levels. This indicates a more desirable use of the Port Mann Bridge capacity. While there is a difference in volume between the predicted 2014 levels and the multi-toll solution on the Alex Fraser Bridge and Massey Tunnel, the LOS experienced on these crossings remain constant.

The traffic distribution for this multi-toll scenario is similar to what was observed in the base year. The largest difference was on the Alex Fraser Bridge. This crossing, however, still handles more traffic than any other, which is consistent with historical observations. This result validates the realistic impacts of our model.

The generated revenue, while not taking into account inflation, changes in traffic volumes, or traffic patterns, is sufficient to cover capital costs alone in under 16 years. While this daily revenue of \$600,000 exceeds the daily requirement, the largest toll applied in this scenario is at least a dollar less than the current toll price on the Port Mann Bridge. The average toll is \$1.64. The model chooses the upper bound on the revenue to allow greater discrepancies between the tolls and this allows the model to solve at a lower minimized total congestion value.

Table 7 displays a sensitivity analysis on the upper bound of the revenue constraint. From this, it is shown that lowering the upper bound from the current \$600,000 lowers the average toll while increasing the congestion factor. Also, an increase of the revenue bound to \$700,000 shows little change in the congestion factor (less than 0.1%) while increasing the toll to \$1.91. It should be noted that the maximum LOS values for each crossing remain unchanged for all four revenue values.

Revenue (\$)	Congestion Factor	Average Toll (\$)
400,000	752767	1.06
500,000	752263	1.04
600,000	740162	1.64
700,000	739636	1.91

Table 7: Sensitivity analysis on revenue upper bound

6 Computational Software

Both scenarios were solved using Microsoft Excel Solver, 2007. Some Solver parameters have been changed from the default settings. The tolerance level was reduced from the default to 1% and the derivative method was changed to central. The maximum time limit was also increased to 200 seconds, although all run times in solving this model never reached this upper bound.

7 Summary

The above analysis offers a multi-toll scenario which results in an increase in overall revenue and a decrease in traffic congestion in the region. The traffic volume distribution is closer to the equilibrium observed prior to the implementation of a toll on the Port Mann Bridge by introducing a new tolling system across the four main Fraser River crossings.

The results of the one toll scenario, namely an increased toll on the Port Mann Bridge to \$3.48 coupled with a minimum average daily revenue of \$330,000 (see Table 5), indicates the need to explore a multi-toll scenario. The multi-toll scenario presented calls for an implementation of tolls on all the crossings. Each toll price is significantly lower than the current toll of \$3.00 on the Port Mann Bridge. This scenario also offers a decrease by almost 12% in the overall congestion factor from what is projected in 2014 while providing a substantial increase in the revenue generated by the tolls (see Table 6).

The implications of the multi-toll scenario imply that a larger portion of the population would be subject to tolls in order to meet revenue requirements and improve regional congestion. However, individual tolls would be lower than the current toll on the Port Mann Bridge. Infrastructure

investments would need to be implemented to allow for tolling on the other crossings. There would also need to be cooperation between the various government authorities involved to enact the recommended tolling system.

While the model utilizes all the data presently available, it could be further enhanced with more complete or expansive data. Information on the entire 2014 year would perhaps be the most influential as the full toll price on the Port Mann Bridge was only recently implemented and there has been a limited time frame for observation to take place. Other data may include AADT for all crossings for a period greater than 10 years or transit utilization crossing the Fraser River. By extending the historical data obtained, a more reliable estimate as to the future requirements of the region would be obtainable. Transit ridership data, which is in the process of becoming documented through a new transit pass system, would assist in predicting the effects of a toll on the volume of passengers using public transit. By accounting for this loss of tolled vehicle traffic, an overestimation of the revenue generated would be less probable and therefore more reliable. Due to the limited historical information that is available and without doing long term traffic projections, the model is taking on a short term perspective. As a result of the reaction to the current toll on the Port Mann Bridge, the Ministry of Transportation has already reduced revenue projections by 20% for the next three years [26]. This further emphasizes the inability to have a reliable long term projection when dealing with considerably unknown reactions.

This model does not divide the total traffic utilizing the various crossings into distinct groups or regions. While this may be able to better predict user preference, it would substantially increase the complexity of the model. Additionally, being able to identify the different groups would be a highly subjective task that would induce unnecessary variability in the solution.

While this model could easily be adapted to changes in infrastructure or other circumstances in Greater Vancouver, revisions would be required for its use in other locations. This is due to the preferences of the population under consideration and their previous experience with tolled roadways. For example, the relationship between traffic volume and toll price observed in Greater Vancouver is most likely more extreme than a region where tolls are already accepted as a societal norm.

A Formulation

A.1 Decision Variables

X_i	Projected AADT for the i^{th} crossing
t_i	Toll on the i^{th} crossing

A.2 Parameters

p_{ijk}	Percentage of the i^{th} crossing's AADT in the j^{th} direction during the k^{th} hour
Y_i	AADT on the i^{th} crossing from the base year 2012
L_{in}	LOS threshold on the i^{th} crossing for the n^{th} level
w_{in}	Congestion weighting on the i^{th} crossing for the n^{th} Level of Service
D	Required average annual daily revenue for the tolling system
R	Maximum daily revenue for the tolling system
V	Total predicted AADT for 2014
α	Margin of difference for lower bounds of AADT for the base year 2012
β	Margin of difference for upper bounds of AADT for the base year 2012

$i = 1, \dots, 4$ for the crossings: Port Mann, Pattullo, Alex Fraser, Massey

$j = 1, \dots, 2$ for the directions: North, South

$k = 1, \dots, 24$ for the hours of the day

$n = A, \dots, E$ for the LOS

A.3 Functions

The congestion weight assigned to the i^{th} crossing in the j^{th} direction during the k^{th} hour

$$C_{ijk}(X_i) = \begin{cases} w_{iA} & \text{if } (X_i p_{ijk}) \leq L_{iA} \\ w_{iA} + (w_{iB} - w_{iA}) \left(\frac{(X_i p_{ijk}) - L_{iA}}{L_{iB} - L_{iA}} \right) & \text{if } L_{iA} < (X_i p_{ijk}) \leq L_{iB} \\ w_{iB} + (w_{iC} - w_{iB}) \left(\frac{(X_i p_{ijk}) - L_{iB}}{L_{iC} - L_{iB}} \right) & \text{if } L_{iB} < (X_i p_{ijk}) \leq L_{iC} \\ w_{iC} + (w_{iD} - w_{iC}) \left(\frac{(X_i p_{ijk}) - L_{iC}}{L_{iD} - L_{iC}} \right) & \text{if } L_{iC} < (X_i p_{ijk}) \leq L_{iD} \\ w_{iD} + (w_{iE} - w_{iD}) \left(\frac{(X_i p_{ijk}) - L_{iD}}{L_{iE} - L_{iD}} \right) & \text{if } L_{iD} < (X_i p_{ijk}) \leq L_{iE} \\ w_{iE} & \text{if } L_{iE} < (X_i p_{ijk}) \end{cases}$$

The Net Toll on the i^{th} crossing

$$N_i(t_1, t_2, t_3, t_4) = \begin{cases} t_1 - \left(\frac{2}{3}t_2 + \frac{1}{3}t_3 \right) & \text{if } i = 1 \\ t_2 - \left(\frac{1}{2}t_1 + \frac{1}{2}t_3 \right) & \text{if } i = 2 \\ t_3 - \left(\frac{1}{4}t_1 + \frac{1}{2}t_2 + \frac{1}{4}t_4 \right) & \text{if } i = 3 \\ t_4 - t_3 & \text{if } i = 4 \end{cases}$$

The Toll to Volume Relationship on the i^{th} crossing for the expected volume given tolls

$$\begin{aligned}
 M_1(N_1, N_2, N_3) &= \begin{cases} Y_1 e^{-0.03N_1} & \text{if } N_1 \geq 0 \\ Y_1 + (1 - e^{-0.03N_1}) \frac{2N_2 Y_2 + N_3 Y_3}{2N_2 + N_3} & \text{if } N_1 < 0 \end{cases} \\
 M_2(N_1, N_2, N_3) &= \begin{cases} Y_2 e^{-0.03N_2} & \text{if } N_2 \geq 0 \\ Y_2 + (1 - e^{-0.03N_2}) \frac{N_1 Y_1 + N_3 Y_3}{N_1 + N_3} & \text{if } N_2 < 0 \end{cases} \\
 M_3(N_1, N_2, N_3, N_4) &= \begin{cases} Y_3 e^{-0.03N_3} & \text{if } N_3 \geq 0 \\ Y_3 + (1 - e^{-0.03N_3}) \frac{N_1 Y_1 + 2N_2 Y_2 + N_4 Y_4}{N_1 + 2N_2 + N_4} & \text{if } N_3 < 0 \end{cases} \\
 M_4(N_3, N_4) &= \begin{cases} Y_4 e^{-0.03N_4} & \text{if } N_4 \geq 0 \\ Y_4 + Y_3(1 - e^{-0.03N_4}) & \text{if } N_4 < 0 \end{cases}
 \end{aligned}$$

B Model

B.1 One Toll Scenario

$$\begin{aligned}
 \min \quad & \sum_{i=1}^4 \sum_{j=1}^2 \sum_{k=1}^{24} C_{ijk}(X'_i) X'_i p_{ijk} \\
 \text{subject to} \quad & Y_1 e^{-0.03t_1} = X'_1 \\
 & X_2 + \frac{2}{3}(Y_1 - X'_1) = X'_2 \\
 & X_3 + \frac{1}{3}(Y_1 - X'_1) = X'_3 \\
 & X_4 = X'_4 \\
 & \sum_{i=1}^4 X'_i \geq V \\
 & 0.966(t_1 X'_1) \geq D \\
 & X_i \geq Y_i(1 - \alpha) \quad i = 2, 3, 4 \\
 & X_i \leq Y_i(1 + \beta) \quad i = 2, 3, 4 \\
 & X_i, t_i \geq 0 \\
 & \forall i = 1, \dots, 4 \\
 & \forall j = 1, \dots, 2 \\
 & \forall k = 1, \dots, 24
 \end{aligned}$$

B.2 Multi-Toll Scenario

$$\begin{aligned}
 \min \quad & \sum_{i=1}^4 \sum_{j=1}^2 \sum_{k=1}^{24} C_{ijk}(X_i)X_i p_{ijk} \\
 \text{subject to} \quad & X_i \leq M_i \\
 & \sum_{i=1}^4 X_i \geq V \\
 & 0.966 \sum_{i=1}^4 (X_i t_i) \geq D \\
 & 0.966 \sum_{i=1}^4 (X_i t_i) \leq R \\
 & X_i \geq Y_i(1 - \alpha) \\
 & X_i \leq Y_i(1 + \beta) \\
 & X_i, t_i \geq 0 \\
 & \forall i = 1, \dots, 4 \\
 & \forall j = 1, \dots, 2 \\
 & \forall k = 1, \dots, 24
 \end{aligned}$$

C Hourly Percentages

P _{ijk}													
Bridge	Direction\Hour	1	2	3	4	5	6	7	8	9	10	11	12
Port Mann	North	0.41%	0.23%	0.20%	0.29%	0.61%	2.35%	2.95%	2.93%	2.83%	2.71%	2.64%	2.62%
	South	0.57%	0.34%	0.24%	0.22%	0.35%	0.89%	2.28%	3.29%	3.08%	2.68%	2.56%	2.70%
Patullo	North	0.40%	0.25%	0.18%	0.23%	0.57%	2.26%	3.93%	3.65%	3.58%	3.13%	2.68%	2.53%
	South	0.61%	0.37%	0.28%	0.22%	0.32%	0.80%	1.96%	2.79%	2.50%	2.16%	2.10%	2.32%
Alex Fraser	North	0.30%	0.19%	0.19%	0.34%	0.73%	2.71%	4.61%	4.56%	4.15%	3.50%	2.78%	2.54%
	South	0.67%	0.41%	0.30%	0.22%	0.27%	0.63%	1.36%	2.28%	2.33%	1.83%	1.77%	1.99%
Massey Tunnel	North	0.41%	0.20%	0.12%	0.10%	0.18%	0.77%	1.47%	1.63%	1.72%	2.24%	2.48%	2.73%
	South	0.26%	0.15%	0.10%	0.15%	0.42%	1.84%	5.20%	5.70%	4.73%	3.64%	3.21%	3.01%

Bridge	Direction\Hour	13	14	15	16	17	18	19	20	21	22	23	24
Port Mann	North	2.60%	2.63%	2.76%	2.98%	3.03%	3.06%	2.70%	1.94%	1.51%	1.42%	1.17%	0.76%
	South	2.91%	3.21%	3.62%	3.92%	3.96%	3.84%	3.27%	2.44%	1.85%	1.82%	1.55%	1.07%
Patullo	North	2.56%	2.65%	2.86%	3.26%	3.48%	3.29%	2.55%	1.86%	1.44%	1.32%	1.10%	0.69%
	South	2.57%	2.79%	3.44%	3.93%	4.09%	3.97%	3.43%	2.49%	1.94%	1.83%	1.45%	1.19%
Alex Fraser	North	2.47%	2.49%	2.65%	2.95%	3.02%	2.97%	2.32%	1.58%	1.20%	1.15%	1.00%	0.63%
	South	2.33%	2.68%	3.78%	4.60%	4.65%	4.52%	3.74%	2.47%	1.79%	1.68%	1.48%	1.19%
Massey Tunnel	North	2.95%	3.28%	3.65%	5.07%	5.49%	5.07%	3.35%	2.09%	1.69%	1.59%	1.24%	0.76%
	South	2.82%	2.68%	2.77%	1.85%	1.79%	1.86%	2.20%	1.59%	1.31%	1.08%	0.87%	0.50%

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