Dynamic tolling of HOT lanes through simulation of expected traffic conditions

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Abstract: *Dynamic tolling of High-Occupancy/Toll lanes (HOTL) is a challenging task, particularly given the range of policy constraints that could potentially be applicable. Methodological literature on the topic is relatively sparse or is considered proprietary information, particularly with respect to current implementations. A framework was developed for the Ministry of Transportation of Ontario (MTO) that utilizes micro-simulation of short-term future conditions to evaluate alternative tolling rate strategies and select the rate to be applied for the next time interval. In this case, the objective of the selection algorithm was the choice of a toll rate that maximized utilization of the HOTL subject to maintenance of a specified minimum average speed. Short-term future conditions can be anticipated by supplying the micro-simulation model with traffic flow data collected "upstream" of the HOTL. The framework, as conceived, has a high degree of flexibility. It could be applied on-line or simulation trials conducted off-line could be used to generate a look-up table relating toll rates to traffic conditions. Measurements of actual HOTL performance under the chosen toll rate could be recorded and generalized using a neural network. Reinforcement learning or other machine learning methods could be applied either on or off-line to improve the decision-making process. The process, including the dynamic pricing algorithm but excluding generalization or learning capabilities, was implemented in AIMSUN for evaluation and trial application. The current paper describes the operation of the framework and its application to the evaluation of a hypothetical HOVL to HOTL conversion.*

1. Introduction

High-Occupancy/Toll lanes or HOT lanes (HOTL) are a relatively recent phenomenon. Most commonly, they are seen as a way of increasing the utilization of existing High-Occupancy Vehicle lanes (HOVL) while maintaining the attractiveness of these lanes for high-occupancy vehicles (HOVs), in terms of reduced travel times. Increasing HOVL utilization represents one means of increasing the effective capacity of a highway corridor. At the same time, HOTLs create an opportunity to generate revenue by providing "premium" service to single-occupant vehicles (SOVs) in return for a toll.

To simultaneously achieve each of these objectives, a dynamic pricing mechanism is required. Such a mechanism ideally establishes a toll rate, at each point in time, which attracts enough paying SOVs to use the excess capacity in the lane, beyond that occupied by the HOV users. At the same time, the toll rate must be such that the HOTL will not become congested to the point that the travel time advantage relative to the remaining unmanaged lanes (general-purpose lanes or GPLs) is lost.

The Ministry of Transportation of Ontario currently operates three HOVL corridors on its 400-series highway system (see Figure 1): on the Queen Elizabeth Way (15.5 km eastbound and westbound, opened in 2010), on Highway 403 (12.5 km eastbound and westbound, opened in 2005) and on Highway 404 (6 km northbound, 10 km southbound, opened beginning in 2005). These HOVL are currently well-utilized, typically attracting from 500 to more than 1,000 veh/h during the peak hours. However, mention of HOTL in a recent Ontario government budget prompted the Ministry to develop a process to evaluate the potential conversion of HOVL to HOTL.

2. Dynamic tolling systems

In many cases, the details of the tolling systems used for existing HOTLs across the United States are considered proprietary information and are not publicly available. However, the following examples illustrate the range of approaches used:

- A static toll rate schedule, with rates varying by time of day, based on experience and updated periodically.
- Dynamic tolling based on speed/volume/density data collected in the HOTL, with toll rates set to maintain a target density or speed.
- Dynamic tolling tied to detection of vehicle platoon formation in the HOTL, indicating the onset of congestion.

Dynamic tolling is used on a number of existing HOTL facilities, including the I-15 in San Diego CA, I-394 in Minneapolis MN (MnPass), WA-167 in Seattle WA and I-95 in Miami FL. Static pricing is used, for example, on the SR-95 in Orange County CA.

3. The development of a dynamic tolling framework

3.1. Desirable features and operating assumptions

Several features were identified as being desirable to guide the process of developing a dynamic HOTL tolling framework.

The toll rates in a dynamic pricing system are set for some short future interval, typically about 5 minutes. It was considered desirable that the toll rates for a given time interval be determined on the basis of the traffic conditions expected for the same time interval, rather than on the basis of traffic conditions observed during a past interval. In a sense, the approach would be pro-active rather than reactive. While current HOTL implementations and most previous research initiatives in this area have typically taken the reactive approach, several recent research efforts (see (3), (8), (9), (11), for example) have pursued a pro-active approach involving short-term traffic forecasts. There appears to be some consensus that the pro-active approach will tend to generate a more stable traffic situation.

It was considered desirable, in combination with the previous point, that the pricing framework consider the relative conditions in the HOTL and GPLs in setting the appropriate toll rate. It is generally agreed that drivers consider traffic conditions in the HOTL relative to those in the GPLS, along with the cost associated with using the HOTL and their personal valuation of travel time, in deciding whether or not to use the HOTL. A number of recent research efforts have incorporated this decision model (see (1), (7), (9), (11), (12), for example). Based on the information available, it appears that the toll rates for current HOTL implementations are determined based on traffic conditions in the HOTL alone: tolls are increased if the HOTL becomes or gives signs of becoming too congested, and decreased if the demand drops. Again, in a sense, this is a reactive approach rather than the pro-active approach proposed. In conjunction with this approach, it was considered desirable to incorporate a realistic depiction of the value-of-time (VoT) for commuters. Much recent research (see (1), (4), (6), (7), (8), (10), (11), (12), for example) has identified reliable representation the heterogeneity of drivers' willingness to pay as a critical component of dynamic pricing.

Given our experience across more than sixty projects using traffic simulation (VISSIM, AIMSUN, and PARAMICS) and our high level of comfort with its transparency and reliability as a traffic analysis tool, it was an obvious extension to apply micro-simulation as a component of this framework. While recent research efforts have included the use of simulation to evaluate the proposed methodologies (see (4), (6), (7), (8), (9), (13), (14), for example), it was considered desirable to investigate the application of simulation as a fundamental component of the framework. Given the accelerated schedule for the project (the target was four months but six months were actually required for concept development, model development, testing, and documentation) it was decided to maximize the use of micro-simulation in preference to working with feedback control or one of the other toll determination approaches reported in the literature.

Certain assumptions and parameters were established as a starting point for evaluation. Toll rates would be set individually for each section of the HOTL between two existing access/egress zones, each section being approximately two kilometres in length. A driver would be assigned the toll rate prevailing upon entry and that rate would be held constant until exiting the HOTL. It was felt that this would minimize driver confusion concerning the toll rate they were being charged. Toll rates would be updated at 5-minute intervals. A minimum toll rate of $0.05/km would be set to discourage casual use. Toll rates would change in nominal $0.05 increments with a maximum increase or decrease of $0.10/km during any given interval.

A target performance standard for the HOTL was set at a minimum speed of 70 km/h, to be achieved at least 90% of the time. This is comparable to the target which is mandated for some HOTLs in the United States. This performance standard is compatible with a HOTL flow rate of approximately 1,600 to 1,700 veh/h, representing the limiting volume before operating speed begins to markedly deteriorate. The operating objective used to set toll rates involved achievement of an average operating speed of as close to 70 km/h as possible without dropping below that limit for any prolonged period. It was assumed that achieving this objective would effectively maximize utilization of the HOTL without seriously impacting its attractiveness to HOVs and paying SOV's.

3.2. Description of the dynamic tolling framework

The proposed dynamic tolling framework is described below and is shown in Figure 2. It is believed, although it cannot be confirmed, that this overall framework represents a unique and innovative approach to the dynamic tolling requirement.

The key features of the proposed framework are as follows:

1. The toll rate to be signed for each section during the next interval ($t_{t,t+5}$) is based on several (up to five) simulations of the highway (HOTL and GPLs) for that interval, with incrementally adjusted toll rates for each section, to determine the toll rate best able to achieve the desired performance standard.
2. Two parallel instances of the simulation model are operated simultaneously. A "shell" instance maintains an ongoing simulation of the traffic state, pausing at 5-minute intervals (t_t) to supply this state information to the second "evaluation" instance. The "evaluation" instance simulates the next interval ($t_{t,t+5}$) under conditions of expected traffic demand, incrementally adjusting the toll rates for the individual HOTL sections in accordance with a pricing algorithm, until the expected operating speed is as close as possible to 70 km/h over all sections of the HOTL. The traffic assignment inherent in this simulation assigns traffic to the HOTL vs. the GPLs in accordance with the drivers' VoTs. The "evaluation" instance passes the selected set of toll rates back to the "shell" instance which then proceeds to simulate the interval ($t_{t,t+5}$) and update its traffic state accordingly. The "shell" and "evaluation" simulation instances could be operated either on-line or off-line, as described later.
3. The selected toll rates would also be passed to the Variable Message Signs informing drivers of the current toll rates. It is anticipated that a VMS at each HOTL entry point would provide drivers with the toll rate prevailing at that entry location plus the total toll to the next exit point and to the end of the HOTL.

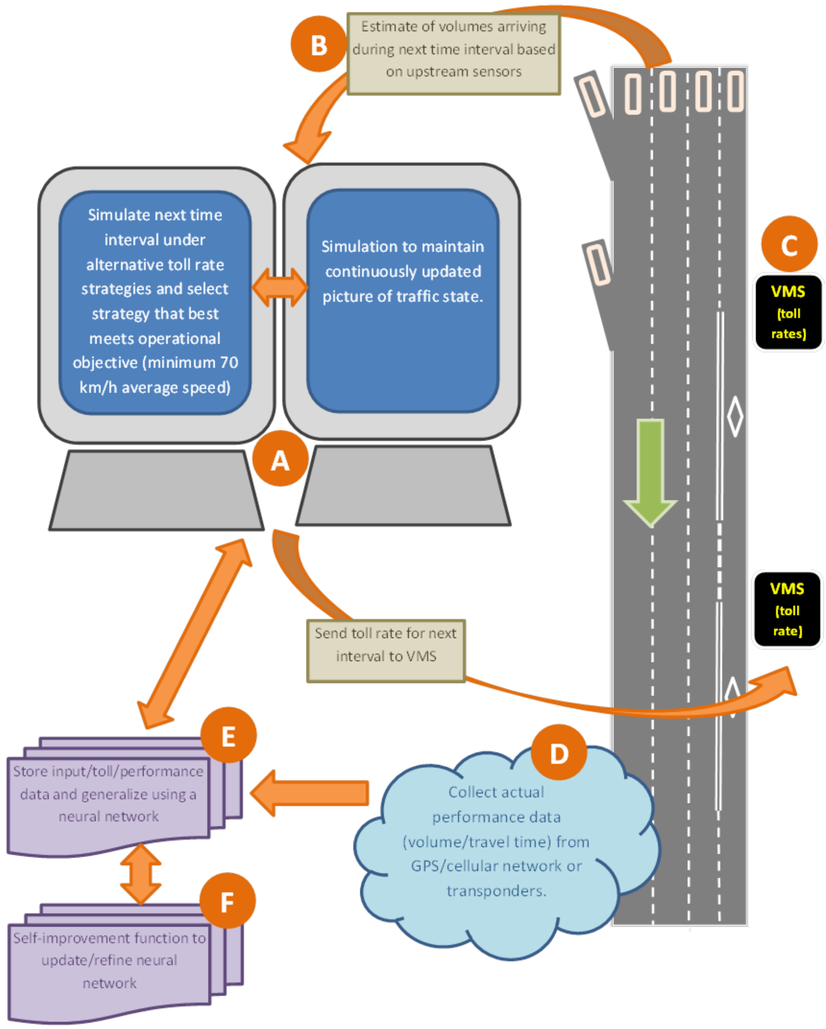

Figure 2: *Dynamic tolling framework schematic*

4. The simulations utilize an underlying set of class-specific demand matrices representing "typical" demand in the corridor. This demand would be adjusted every 5 minutes in real time to facilitate an estimate of short-term future conditions based on the outputs from volume sensors at appropriate locations upstream.
5. After each 5-minute interval, traffic volumes and travel times would be recorded for the HOTL and GPLs, along with the toll-rates used. Volumes could be recorded using loops and travel times using real-time GPS/cellular data. These volumes, in addition to their application as discussed in the following point, could be fed back into the "shell" instance of the simulation to correct for any deviations from actual traffic flows.
6. Over time, the data from the previous point would be fused/generalized using a neural network (15) or similar generalization tool. For those unfamiliar with the concept of neural networks, they would, in this context, parallel the generalization or pattern recognition function of multiple regression but without comparable constraints on the form of the relationships between the dependent and independent variables. A neural network could be combined with a reinforcement learning algorithm (17) to create a tool that could "learn" the best toll-rate strategy for all potential traffic states based on real-time or simulated "training". This learned strategy could be retained as a back-

up for on-line implementation, in the event of technical problems, or could be used as a look-up table to set the toll rates as a standalone methodology. In fact, the neural network could be "trained" off-line, prior to implementation, using a reinforcement learning algorithm in conjunction with micro-simulation. If implemented as a look-up table, the neural network could, over time, be fine-tuned and updated using data collected on an ongoing basis or through periodic on-line "episodes".

7. Initially, the VoT distribution used in the framework would be based on a stated-preference survey and, in fact, such a survey was conducted for the Ministry by IBI Group and was used in this evaluation. However, the data collection, fusion, and generalization described in the previous two points could be readily used to fine-tune the VoT distribution based on preferences revealed by actual HOTL users relative to actual traffic conditions and toll rates.

The framework has a high degree of inherent flexibility that allows it to be operated in a variety of modes depending on user requirements and hardware/communications availability. Some available operational modes are shown in Table 2 with reference to the labelled components of Figure 2.

Table 1: *Alternative operational modes for the proposed framework*

Mode of use	Components used (from Figure 2)					
	A Parallel simulations to maintain traffic state and set toll rates	B Forecasting of traffic demand during next interval	C Variable message signs to display toll rates	D Collection and fusion of performance data	E Generalization of inputs and performance (neural network)	F Self-improvement of neural network (reinforcement learning)
1. Off-line framework evaluation and testing.	✓					
2. Real-time, on-line dynamic pricing	✓	✓	✓			
3. Real-time, on-line dynamic pricing plus maintain a back-up neural network (look-up table) to cope with system downtime.	✓	✓	✓	✓	✓	✓
4. Off-line development of a neural network (look-up table) to be used in real time to set tolls.	✓		✓		✓	
5. Off-line development of a neural network (look-up table) with periodic on-line episodes for updating.	✓	✓	✓	✓	✓	✓

3.3. Description of the algorithm used to set the toll rates

An algorithm was developed to set the toll rates for each section of the HOTL for a given 5-minute time interval (collectively known as a tolling "strategy"). In fact, there are two versions of the algorithm, one for testing scenarios where the toll rate is constant over the entire HOTL and one where the toll rate varies by section.

There are several complexities that affect both the design of the algorithms and also their effectiveness in achieving the utilization and operating (minimum speed) objectives. First, the multiple sections (up to eight) in each of the hypothetical HOTL corridors being evaluated represents a more complex situation than those HOTL implementations that have only a single section, requiring a single toll rate, or a very few sections or zones. The fact that tolls are held fixed for individual drivers once they enter the HOTL, until they leave the HOTL, means that toll rate changes influence only those drivers about to enter the HOTL – those that are already in the HOTL are unaffected, at least directly, by toll rate changes. The use of the HOTL by a substantial number of HOVs reduces the proportion of drivers in the HOTL directly influenced by toll rate changes. The algorithm used for scenarios where the toll rate was held constant along the length of the HOTL, in addition to being constant for each driver, is obviously operating under fairly significant constraints in terms of influencing drivers' use (or not) of the HOTL. It is unlikely that a single toll rate along the length of the corridor would represent the best solution for each section of the corridor.

Both versions of the algorithm have the same basic steps. Toll rates for sections of the HOTL operating with speeds above 70 km/h are initially reduced until either the maximum decrease in toll rate per interval is reached or the speed drops below 70 km/h. The next step involves increasing the toll rate for sections operating with speeds below 70 km/h until either the maximum increase in toll rate per interval is reached or the speed meets the 70 km/h minimum standard. To address the constraints discussed in the previous points, intermediate steps were included whereby toll rate changes for specific sections were supplemented by additional changes affecting upstream HOTL sections pre-selected by the user. The actual definition of sections to be so affected could be fine-tuned based on the demand patterns within a given corridor. However, for the purpose of this evaluation, the next upstream section was defined initially for supplementary rate changes. Based on initial trials, this was changed to the furthest upstream section.

There is likely headroom to refine these algorithms. However, for the purpose of initial evaluation of the framework, the algorithms used (see Figures 3 and 4) proved to be reasonably effective, given the challenging circumstances.

4. Implementation of the dynamic tolling framework for evaluation

Selected components of the framework were implemented for evaluation purposes in the AIMSUN environment by TSS - Transport Simulation Systems. The "shell" and "evaluation" instances of the simulation environment were implemented, along with the programming needed to implement the communication and interaction between them. The algorithms required to set the toll rates dynamically were included in the "evaluation" instance. Modifications to the stock AIMSUN dynamic assignment algorithm were implemented as required to evaluate travel time and cost in the context of VoT, and implement the appropriate route choices. Finally, data detector capabilities within AIMSUN were modified to collect the required outputs for analysis.

The implemented components included a number of user-specified parameters to provide flexibility to the user, such as the eligibility of different vehicle classes to use the HOTL and the associated percentage of the full toll rate to be applied by class, as well as maximum and minimum toll rates and toll rate increments.

Certain additional modifications to the AIMSUN software were required to address specific issues identified during the evaluation. For example, it was found that changing traffic conditions and toll rates could, even with relatively insignificant changes, result in an unreasonably high number of entries to and exits from the HOTL, leading to additional congestion in both the HOTL and GPLs. It was necessary to include a user-adjustable "laziness" or inertia variable that would tend to limit the propensity to enter or exit the HOTL with only small changes in conditions.

Certain components, conceptualized as part of the proposed framework, were not required for evaluation purposes and therefore have not yet been implemented although, in some cases, their suitability has been demonstrated in other applications. It was unnecessary to include the short-term traffic forecasting component as travel demand over time could be completely pre-specified for evaluation purposes. Although a specific approach has not been defined for this process, a relatively simple factoring process based on strategically located upstream loops or other detectors could be used, recognizing that each short-term forecast (about 5 minutes) can be replaced with the actual volume once it has occurred so that the potential for significant deviation from reality is small. Data fusion and generalization using a neural network, in combination with reinforcement learning, was not implemented in this case. This process has previously been demonstrated in the context of intelligent, adaptive traffic signals (17) where a relatively straightforward neural network known as a Cerebellar Model Articulation Controller (CMAC) (18), (19) was used in conjunction with the variant of reinforcement learning known as Q-learning (20).

5. Evaluation process

For evaluation purposes, the dynamic tolling framework was applied to hypothetical HOTL conversions of several existing HOVL corridors in the Greater Toronto Area. Six-hour periods in both the morning and afternoon were simulated, assuming these would cover the periods during which drivers might be willing to pay a toll to avoid congestion. A variety of scenarios was simulated to evaluate the range of capabilities of the framework and its component methodologies. Some scenarios assumed toll rates specific to each HOTL section while others assumed a constant toll rate over the length of the HOTL. Eligibility criteria were varied with respect to HOV2s with some scenarios allowing them to use the HOTL free while others required payment of 50% or 100% of the toll paid by SOVs. In some cases, the toll rate was capped while in others, it was unconstrained. Variations on the VoT distribution were evaluated, along with alternate minimum toll rates. While most of the evaluation was conducted with a performance standard of 70 km/h, a "buffer" was added in some scenarios, increasing the target speed to 85 km/h.

Apart from several required modifications to the framework as identified in the previous section, a structured program of evaluation and refinements has not yet been undertaken. Furthermore, there has been no attempt to customize the framework to better suit specific highway corridors. Sensitivity to alternative demand scenarios has not been evaluated with respect to the hypothetical situations evaluated.

6. Evaluation results

This section reports selected results – those oriented to evaluation of the performance of the dynamic tolling framework. The results shown are a sample representing a corridor where the level of traffic demand is generally appropriate for the introduction of HOTLs. The broader results obtained across the range of scenarios tested were not universally "optimal". Where traffic demand was only marginally over-capacity without HOTLs, HOTL utilization and related benefits would obviously be reduced. This could have been addressed to a greater or lesser extent by allowing demand to re-reroute between highway corridors to backfill the additional capacity accessed through conversion of HOVLs to HOTLs. Different levels of future growth in demand could also have been evaluated. However, neither of these extensions of the evaluation process has been undertaken. Where the physical configuration of the HOVLs resulted in congestion in these lanes today, the benefits associated with the implementation of HOTLs would also be limited. It is apparent that HOTL implementation would have to be evaluated on a case-by-case basis to evaluate the expected benefit. HOTLs do not represent a panacea in the context of traffic congestion.

The results shown typically compare three cases, an HOVL, a HOTL where HOV2+ are eligible without paying the toll (HOTL/HOV2+), and a HOTL where HOV3+ are eligible without paying a toll (HOTL/HOV3+). Assumptions used in the generation of these results included variation of toll rate by section, no capping of the toll rate, a 70 km/h performance standard for the HOTL, and adjustment of existing (2011) travel demand to include five years' growth.

6.1. HOTL Utilization

As noted previously, one of the key objectives of implementing a HOTL would be to improve the utilization of existing HOVLs. Therefore increasing utilization to a level consistent with the 70 km/h performance standard (or the equivalent "capacity" would represent an optimum result.

Figures 3, 4, and 5 represent three different metrics for HOVL/HOTL utilization. Figure 3 shows the actual changes in the average traffic volume in the lane when converted from an HOVL to an HOTL/HOV2+ or a HOTL/HOV3+. Figure 3 shows that the peak-hour, peak-direction utilization of the lane increased by 77% when converted from an HOVL to a HOTL/HOV2+, from an average of 905 veh/h to 1,600 veh/h, or the approximate capacity equivalent to a performance standard of 70 km/h. When converted to a HOTL/HOV3+, the peak-hour, peak-direction increased by marginally less (70%), due to the fact that SOVs using the lane were offset to some extent by HOV2s leaving the lane since they were required to pay the same toll as SOV's.

Figure 4 shows the average peak-hour, peak-direction utilization measured as a percentage of the total available hourly veh-km of travel based on a "capacity" of 1,600 veh/h. Conversion of an HOVL to a HOTL/HOV2+ results in an increase from 57% to 100% utilization whereas conversion to a HOTL/HOV3+ results in an increase to 95%.

Figure 5 shows the utilization expressed in terms of the total person-km observed in the lane in the peak direction during the peak hour. Conversion of an HOVL to a HOTL/HOV2+ results in a 29% increase while the corresponding increase for conversion to a HOTL/HOV3+ was 6%, again due to the relevant eligibility criteria.

It is apparent that the conversion to a HOTL using the proposed dynamic tolling approach was successful in increasing utilization of the lane. In fact, in the case of conversion to a HOTL/HOV2+, full utilization was achieved. Conversion to a HOTL/HOV3+ was only marginally less successful, primarily due to the tolling and resultant loss of HOV2s. Achieving full utilization also increased the number of person-km in the lane, although not proportionately since the added vehicles were SOVs.

6.2. Traffic Speed in the HOVL/HOTL vs. the GPL's

On the basis of the average traffic speed in the HOTL, achieving an average speed of at least 70 km/h, but staying close to that mark, would represent an optimal result. Additionally, it is obviously desirable to maintain a positive speed differential in the HOTL relative to the GPLs to ensure that users are obtaining value in return for paying the toll.

Figure 6 shows that the average speed in the HOTL/HOV2+ was 78 km/h while that in the HOTL/HOV3+ was 91 km/h, relative to the average of 89 km/h for the original HOVL. The fact that these average speeds are noticeably above the 70 km/h performance standard suggests perhaps that there is some scope to further optimize the utilization of the HOTLs. The improvement of the GPL speeds observed with conversion to HOTLs and the additional capacity opened up in the HOTLs suggests that higher demand levels than those evaluated might be accommodated. However, taking into account the volatility of GPL speeds on a congested highway, commonly hypothesized relationships between speed and flow rate, the effect of reductions in average speed in the vicinity of access/egress zones, and the fact that utilization and speed vary along the length of a HOTL with multiple access/egress locations, it is also possible that increases in utilization may trigger a significant drop in speed. It is therefore not possible to draw any significant inferences in this regard without further analysis. It is noted, however, that a differential of at least 6 km/h is maintained between the HOTL and the GPLs although this differential will vary from section to section and over time.

6.3. Compliance with the Performance (Minimum Speed) Standard

Figure 8 summarizes the compliance with the assumed speed standard for the HOTL, namely maintenance of a 70 km/h average speed in the HOTLs at least 90 per cent of the time. Compliance was evaluated on the basis of the speeds for each HOTL section for 5-minute intervals during the peak hours and in the peak directions.

Figure 8 shows that in three out of four peak-hour, peak-direction cases for the representative corridor reported here, the compliance exceeded the desired 90 per cent. In one case, the compliance was 75 per cent. While these results are promising, there is still some scope for fine-tuning of the framework. In particular, improving operation in the vicinity of the access/egress zones is one area where a potential for refinement was noted. It was found that the use of a performance standard of 85 km/h led to lower compliance levels although the possibility of a marginal increase in the standard to provide a “buffer” has not yet been investigated.

6.4. Traffic Composition in the HOTLs

Although only indirectly tied to the objectives for the hypothetical HOTL conversions evaluated, it is nonetheless interesting to observe the implications for the composition of the traffic flow in the HOTL in terms of SOVs vs. HOV2s vs. HOV3+s. Figures 8 and 9 summarize results for the peak directions in a representative corridor for the morning and afternoon peak hours respectively. For the HOTL/HOV2+

case, there is a marginal decrease in the HOV proportions once SOVs are allowed to use the lane. However, as might be expected, when HOV2s are tolled as well in the case of the HOTL/HOV3+ conversion, the reduction in the proportion of HOV2s is substantial. Note that the reaction of HOV2s and HOV3+s to the HOTL/HOV3+ conversion, in terms of the proportion of these carpools in the corridor, was based on some observations elsewhere and relatively simplistic assumptions although the use of the HOTL by these groups remained dependent on traffic conditions in the HOTLs and GPLs and the relevant VoT characteristics.

7. Future work

The effort documented in this paper may be considered as a proof-of-concept evaluation. There are a number of useful directions for further investigation, both in terms of implementing and evaluating the framework components not yet pursued and enhancement of the concept and its implementation.

As noted previously, this project focused on the development and evaluation of the dynamic pricing methodology and did not include actual implementation and testing of components not required to conduct the basic evaluation. Yet to be incorporated in the framework are the traffic demand forecasting component, a process to update the simulation instance tracking the actual traffic state based on actual observations, and the neural network (look-up table) generalization component and its accompanying reinforcement learning "training" feature.

There is headroom for further enhancement of the pricing algorithm, both in terms of the current process flow and, potentially, with respect to the possibility of fine-tuning this algorithm to address the characteristics of individual HOTL corridors. There is a need to investigate improvements to the assignment algorithms used in traffic simulation suites as noted previously in the context of HOTL modelling.

Beyond these major directions for future work, there are likely many opportunities to refine the methodology itself once free of the constraints posed by an aggressive schedule.

8. Conclusions

An innovative approach has been proposed to address the need for dynamic setting of toll rates in conjunction with the hypothetical conversion of HOVL to HOTL to increase lane utilization and realize potential revenue. This framework has been implemented to an extent sufficient to permit preliminary evaluation for several hypothetical situations using micro-simulation.

The proposed framework represents a flexible approach to the dynamic toll rate problem with a number of possible implementation modes, depending on the requirements of a specific case.

It was found that the framework, as evaluated, represents a promising approach to this complex issue, producing satisfactory results with only very limited refinement and no tailoring of the approach to address specific corridor characteristics. There is headroom for further refinement of the framework, both in terms of specific algorithms and in terms of how the framework might be customized to a particular situation.

It is believed that the approach proposed here represents a promising advancement in the context of the current body of knowledge in this area. Further refinement and evaluation of the framework is required to confirm this belief.

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Figures

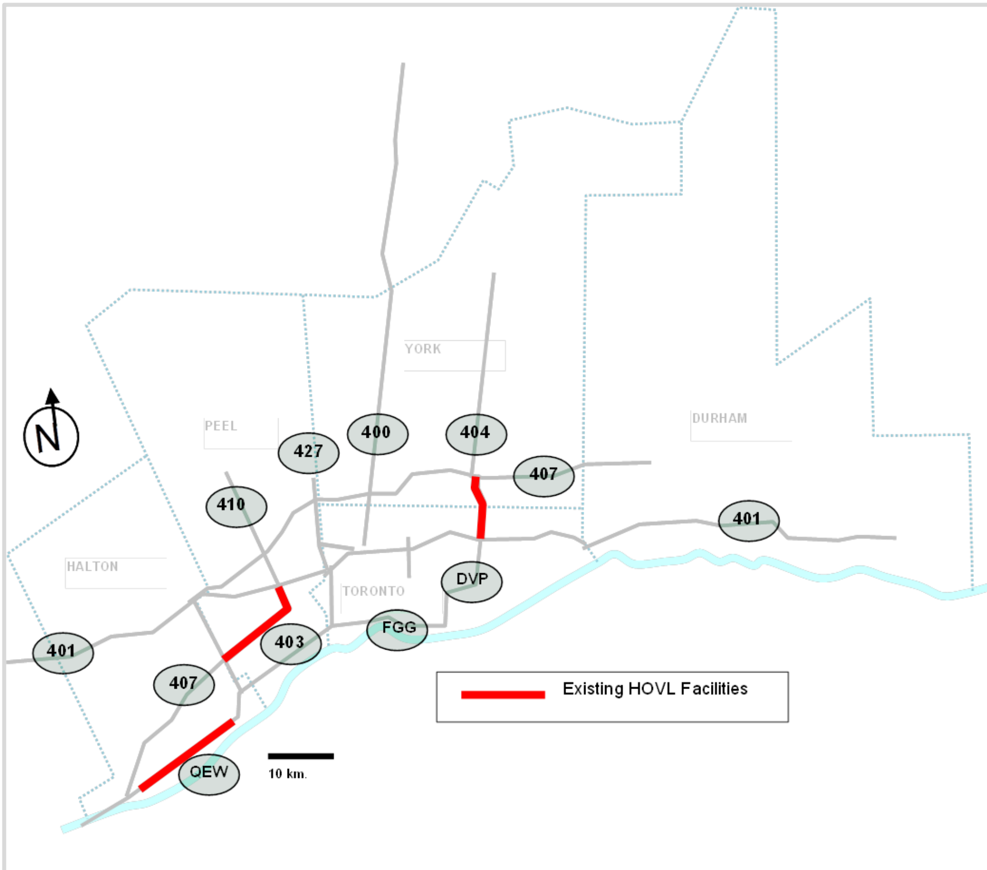

Figure 1: *Existing HOVL corridors in the GTA*

Figure 2 is included with the text to enhance clarity.

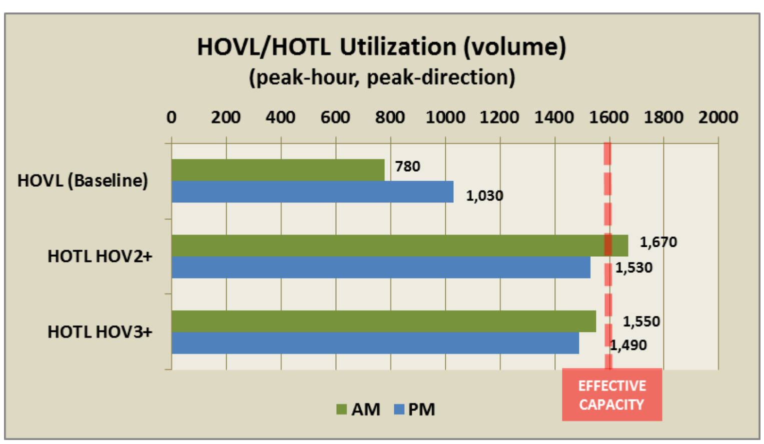

Figure 3: *Comparative utilization of HOVLs vs. HOTLs in terms of traffic volumes*

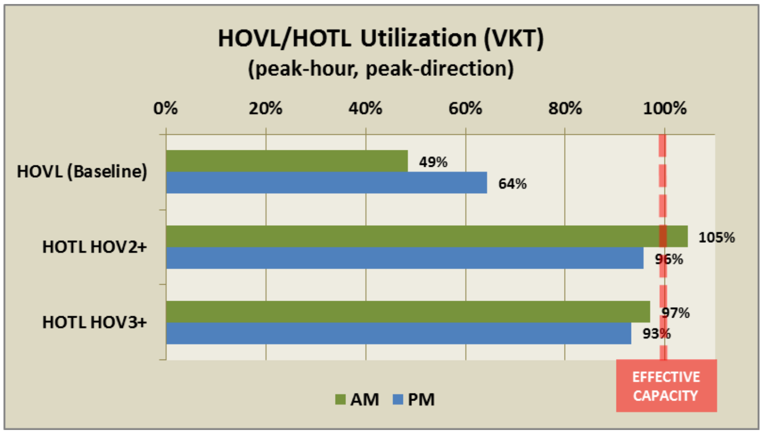

Figure 4: *Comparative utilization of HOVLs vs. HOTLs in terms of vehicle-kilometres of travel*

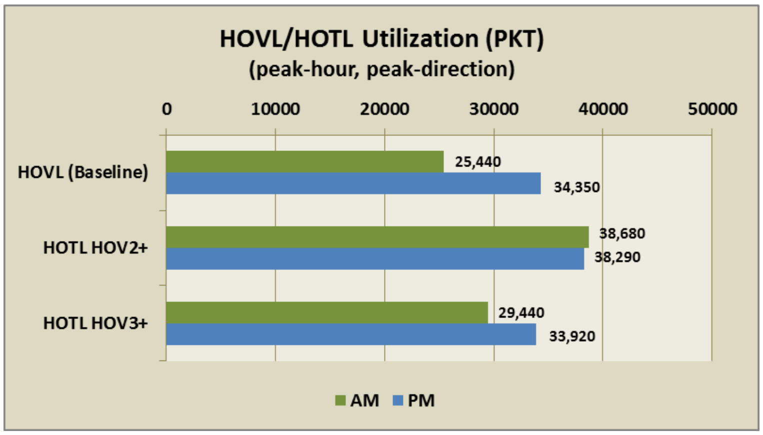

Figure 5: *Comparative utilization of HOVLs vs. HOTLs in terms of person-kilometres of travel*

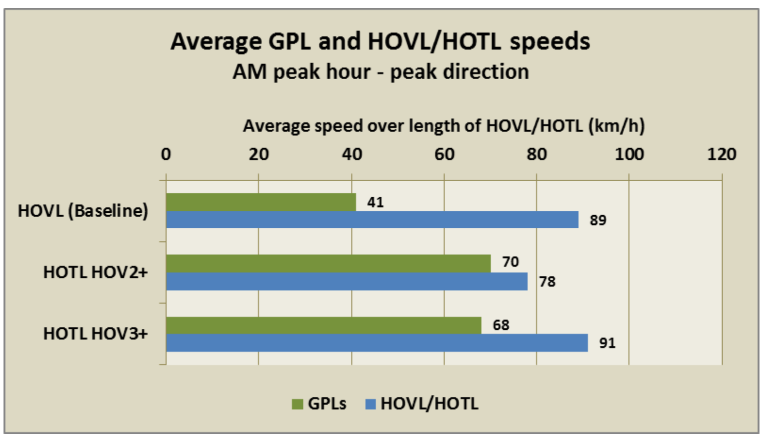

Figure 6: *Comparative speeds in the HOVLs and HOTLs relative to the GPLs – morning peak hour*

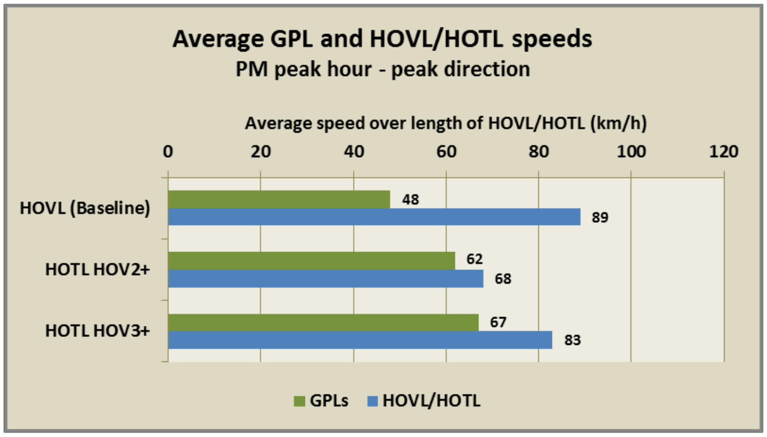

Figure 7: *Comparative speeds in the HOVLs and HOTLs relative to the GPLs – afternoon peak hour*

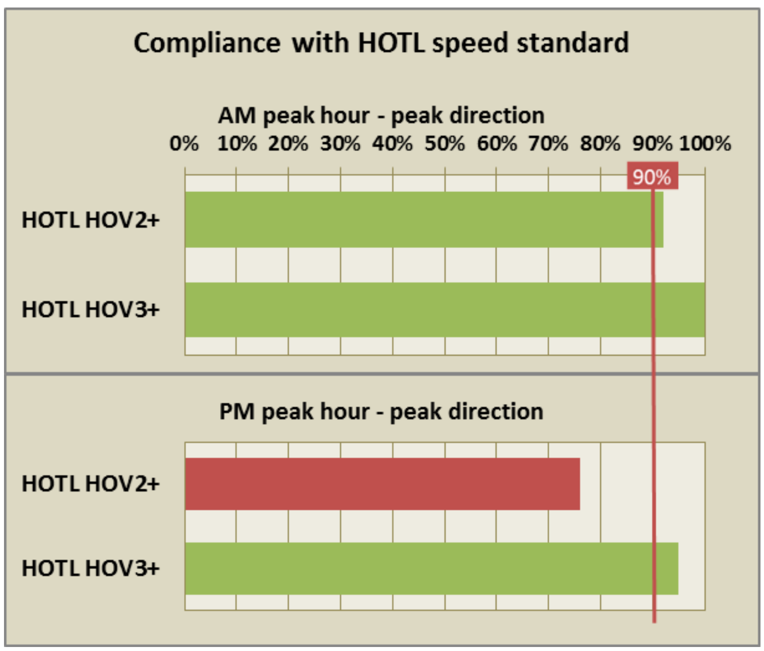

Figure 8: *Compliance with the 70 km/h performance standard in the HOTLs*

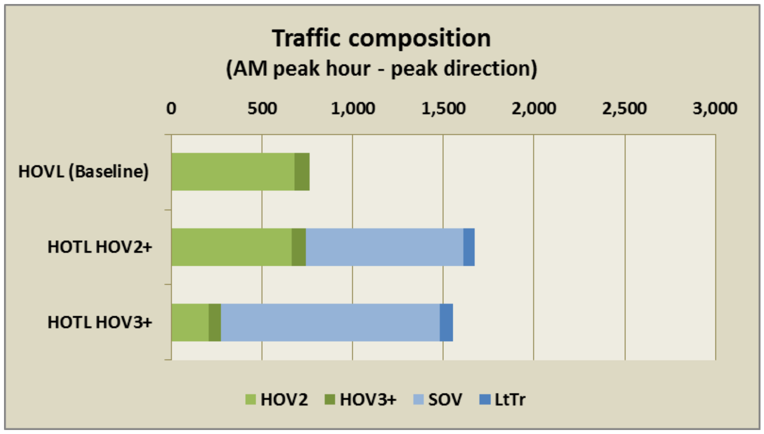

Figure 9: *Traffic composition in the HOVLs vs. HOTLs – morning peak hour*

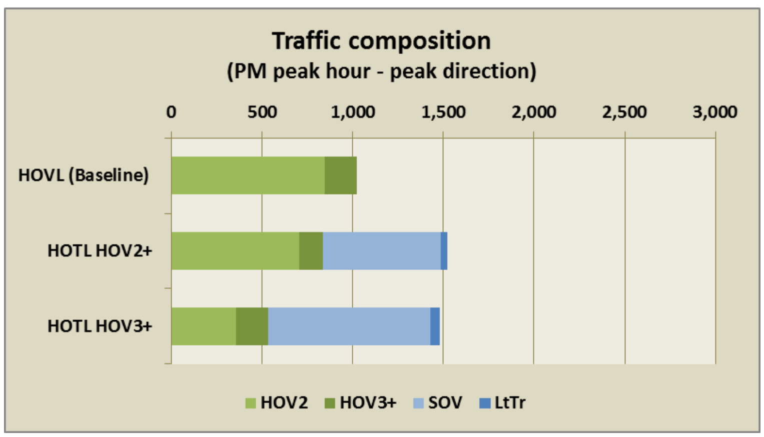

Figure 10: *Traffic composition in the HOVLs vs. HOTLs – afternoon peak hour*