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Advanced Toll Information System and Toll Lane Configuration to Reduce Collision Risk

By

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Windsor, Ontario, Canada

2022

Advanced Toll Information System and Toll Lane Configuration to Reduce Collision Risk

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August 17, 2022

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ABSTRACT

This study assessed the impacts of presence and location of the toll information system on the traffic performance and safety at toll plaza on the Gordie Howe International Bridge. The toll information displays the information on toll payment methods (manual toll collection (MTC), automatic toll collection (ATC) and electronic toll collection (ETC)) for cars or heavy vehicles (HV) via variable message signs (VMS) upstream of toll booth. The study also assessed the impacts of the toll information system with different toll lane configuration for current traffic demand and different percentages of heavy vehicles (HV) to reduce the collision risk at toll plaza. To evaluate the impacts, three scenarios (no VMS, VMS 140 m from the entry gate, and separate VMS for car and HV 75 m before the merge point) were developed and compared using the VISSM microscopic traffic simulation model. Results show that VMS before the merge point had marginal benefit of reducing average delay and reduced rear-end and lane-change collision risk compared to the no VMS scenario. Results also show that converting the toll lanes with multiple toll payment methods to ETC-only lanes with the VMS before the merge point reduced the delay and rear-end and lane-change collision risk compared to the current configuration. Moreover, increasing the number of HV-only lanes from 3 to 4 for higher percentage of HVs with the VMS before the merge point marginally reduced the delay but increased lane-change collision risk compared to the current configuration. This indicates that the installation of ETC-only lanes can potentially improve traffic performance and safety for the current traffic demand but increasing the number of HV-only lanes for higher percentage of HVs can degrade the safety benefit of the system. This study demonstrates that toll lane configuration must be controlled to accommodate varying traffic demand to enhance the effectiveness the toll information system in improving traffic performance and safety.

DEDICATION

I would like to dedicate my thesis to my parents who supported me to pursue a master degree in civil engineering and for their unconditional support and pure love throughout my life.

ACKNOWLEDGMENTS

I would like to give my gratitude to everyone who helped me and have contributed to the development of this thesis. Especially I would like to thank Dr. Chris Lee, my academic advisor, for providing me the opportunity to pursue a master degree at the University of Windsor. His guidance and support helped me to conduct my research and I appreciate the time and effort he took on every step of my research. I am also thankful to my thesis committee members, Dr. Yong Hoon Kim and Dr. Xiaolei Guo who have attended my thesis proposal presentation and gave useful comments and suggestions regarding this thesis. Also, I would like to acknowledge Anas Abdulghani for his help in simulation and developing the project and guiding me on how to use VISSIM, and the Windsor-Detroit Bridge Authority (WDBA) for providing the required data and supporting the research group during the project.

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1. INTRODUCTION

Toll plazas are one of the most critical components of a roadway system for capital financing and ongoing infrastructure maintenance revenue. In Canada, toll roads/bridges and other toll facilities have been in operation in Ontario, Quebec, Nova Scotia and Prince Edward Island (TollGuru, 2022). In particular, toll has been charged to all cross-border traffic at 11 bridges and 1 tunnel at Canada-U.S. international border crossing. Tolls have been manually collected in cash, credit card, prepaid card or also automatically charged using a transponder or by detecting vehicle license plates.

However, although toll plazas have been designed and constructed for a long time, there are no widely accepted design standards for toll plaza uniformity or safety. Due to a lack of standards, there is a growing concern with safety at toll plaza. For instance, some crashes have occurred at toll roads in Canada. They were mostly high-speed-related crashes and lane-change-related crashes at toll plazas which caused death, injury and also extensive damage to the toll booths following the closure of some of the tollbooths (CTV News, 2022).

In this regard, researchers for the U.S. National Traffic Safety Board (NTSB) reported that the most dangerous locations on the highways are toll plazas. In 2006, 49% of crashes on expressways in Illinois occurred at toll plazas and fatality of these crashes were three times higher than fatality of the crashes on the rest of expressways (NTSB, 2017). Also, 30% of crashes on the Pennsylvania Turnpike and 38% of crashes on New Jersey toll highways occurred at toll plazas (NTSB, 2017). A noticeable increase in the number of crashes at toll plazas particularly upstream of toll plazas has generated the need for studying drivers' behaviour as drivers approach toll plazas (Abdelwahab et al., 2012).

To reduce the delay at toll plazas, new tolling technologies such as electronic toll collection (ETC) have been in operation at toll plazas. ETC is an automated system that allows drivers to pay tolls without stopping. ETC consists of a transponder placed inside the vehicle and is activated when the vehicle passes a roadside sensor at the toll booth (Coelho et al., 2005). ETC has numerous benefits such as lower transaction time, improved throughput, and reduced air pollution and fuel consumption (Yang et al., 2014).

However, there are still drivers who manually pay tolls by cash or credit cards. These drivers may be distracted when they search for cash or cards and take time to change to toll lanes which accept manual payment. These behaviours affect drivers' perception and reaction time, and consequently road safety (Valdés et al., 2016). Moreover, when there are both ETC and manual toll collection lanes in the toll plaza (called hybrid toll plaza), drivers are more likely to abruptly change lanes to select the toll lane of their preference.

One solution for this problem is to use toll information system which can help drivers prepare to move to the correct lane or path to the open toll booths with their preferred payment method. There are two types of toll information system – 1) the conventional toll information system which displays toll lane configuration (e.g., the method of toll payment, the type of vehicle) via static signs and 2) the advanced toll information system which displays real-time status of toll lane configuration (e.g., open/close toll booth, re-allocation of toll booths for different payment methods) via variable message signs (VMS). Thus, it is important to determine the optimal location of VMS to provide the toll information to drivers such that they can choose the toll lane of their preference in advance and avoid abrupt speed reduction and lane changes near the toll booth which disrupt traffic flow and increase collision risk (Zhang et al., 2020).

Previous studies investigated the impact of static signs and VMS on the performance and safety of toll plaza. Valdés et al. (2016) compared two configurations of toll information system in Puerto Rico – 1) configuration with roadside signage and 2) configuration with overhead signage - using a cockpit driving simulator. Results showed that the configuration with overhead signage was safer than the configuration with roadside signage. Moreover, Saad et al. (2019) assessed how the route choice, segment length, traffic conditions, and traffic control treatments such as overhead signs and dynamic message sign (DMS) affect the driving behavior at a hybrid toll plaza in Central Florida using a driving simulator. It was recommended to use DMS instead of static signs and adjust the current locations of overhead signs to guide drivers safely.

Based on the literature review, the impacts of location of toll information system and the type of messages such as toll lane configuration on the driver behaviour and road safety has not been studied extensively. Moreover, since most studies considered toll plazas on conventional highways, the findings in these studies may not be applicable to the toll plazas on different types of roads such as a bridge at a border crossing. For instance, the toll plaza at a border crossing has more complex toll lane configuration due to toll lanes designated for a specific vehicle type (car or heavy vehicle), higher percentage of commercial vehicles and trucks, and more variety of toll payment methods. Therefore, there is a need to develop the toll information system which displays toll lane configuration ahead of toll plaza at a border crossing and assess the impacts of toll information system on traffic performance and collision risk at toll plaza.

Thus, the objectives of this study are 1) to assess the impacts of location of the toll information system on the traffic performance and the collision risk at toll plaza and 2) to develop the method of controlling toll lane configuration using the toll information system to reduce the collision risk at toll plaza in varying traffic demand.

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2. LITERATURE REVIEW

This chapter reviews the literature on operation and safety of toll plaza. First, the existing toll information system and the effects of the system on safety will be discussed. Second, the safety evaluation of toll plaza using crash data and vehicle trajectory data will be discussed. Third, the safety surrogate measures which are used to evaluate the level of safety will be reviewed. Lastly, the effects of toll plaza design on operation will be discussed.

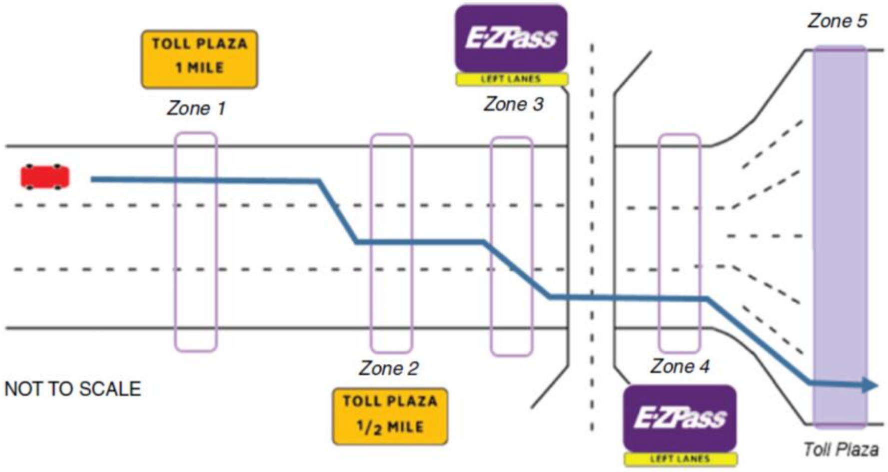
2.1. Toll Information System

The purpose of toll information system is to assist drivers to safely select the lane(s) for their preferred method of toll payment. For this task, the system displays the information on toll lane configuration (e.g., cash or electronic payment lane, lane for cars or heavy vehicles), the status of toll booth (e.g., open or closed), and the amount of toll.

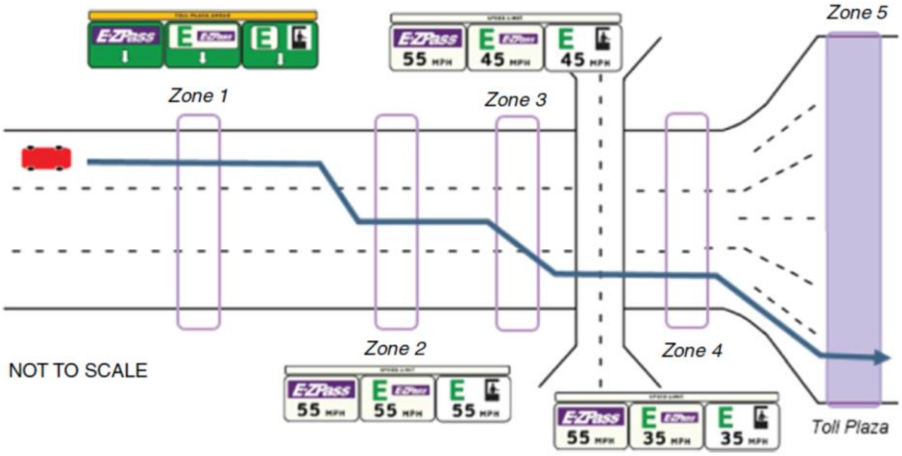
There are two types of signs in the toll information system: 1) static message sign and 2) variable message sign (VMS). Figure 2-1 shows an example of static message signs which display a diverging point between cash payment lane and electronic payment (pre-paid) lanes.

FIGURE 2-1. STATIC SIGN OF TOLL INFORMATION SYSTEM (SOURCE: ABUZWIDAH ET AL., 2018)

Some studies assessed the impact of static message signs on operation and safety of the toll plaza. For instance, Valdés et al. (2016) compared two configurations of static signs at the toll plaza in Puerto Rico as shown in Figure 2-2. The first configuration (current configuration) included the roadside signs which display the distance to the toll plaza, the location of the E-ZPass (electronic payment) lane, and the posted speed limit for the freeway segment. In addition to these, the second configuration included the overhead signs indicating the locations of both E-ZPass and cash payment lanes. The result of this study shows that the second configuration was safer than the current configuration.



(a) Current configuration with roadside signs

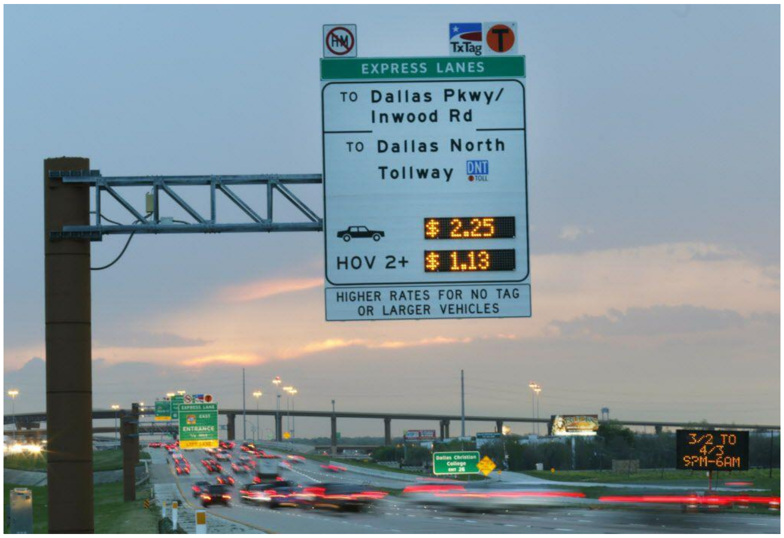


***(b)** Proposed configuration with overhead signs*

Figure 2-2. Static message signs at toll plaza in Puerto Rico (Source: Valdés et al., 2016)

Figure 2-3 shows examples of VMS which displays the status of electronic payment (pre-paid) lanes (Figure 2-3 (a)) and the amount of toll for different vehicle types (Figure 2-3 (b)). These variable message signs can provide drivers with real-time toll information which can vary over time.

(a) Status of toll lane (Source: Abuzwidah et al., 2018)



(b) AMOUNT OF TOLL (SOURCE: DALLAS MORNING NEWS, 2016)

FIGURE 2-3. VARIABLE MESSAGE SIGNS AT THE TOLL PLAZA

Some studies analyzed the effects of VMS on safety at toll plaza. For instance, Saad et al. (2019) assessed how the information for ramp traffic provided via a portable VMS affect driver behaviour at toll plaza using a driving simulator. Figure 2-4 shows the message displayed on the portable VMS. It was found that VMS effectively kept the vehicles from the on-ramp to the toll plaza in the rightmost lane and reduced lane changing before the toll plaza. The study suggested reducing abrupt lane changing before entering the toll plaza can improve safety.

Figure 2-4. Variable message sign for ramp vehicles at toll plaza (Source: Saad et al., 2019)

2.2. Safety Analysis of Toll Plaza

2.2.1. Safety analysis using crash data

Several studies assessed safety of toll plaza using historical crash data. For instance, Abdelwahab et al. (2002) studied traffic safety at toll plazas using the 1999 and 2000 traffic crash reports of the Central Florida expressway system. The results showed that vehicles equipped with ETC (e.g., payment by cash or credit card) devices, especially trucks, were more likely to be involved in crashes at the toll plaza than vehicles without ETC devices. This is potentially because ETC users cannot avoid crashes when ETC lanes are blocked by non-ETC users while they do not anticipate that they should reduce speed or stop at the toll booth. For a similar reason, ETC users are more likely to be severely injured than non-ETC users.

Abuzwidah and Abdel-Aty (2018) evaluated safety impact of different designs of the Hybrid Toll Plaza (HTP) using safety performance Functions (SPFs). A safety performance function is a crash prediction model which relates the frequency of crashes to traffic and the roadway characteristics. They found from the result of SPFs that the risk of crashes was

19 percent higher for a configuration which combines express Open Road Tolling (ORT) lanes (i.e., electronic toll payment lanes) in the mainline and separate traditional (i.e., manual) toll collection lanes to the side than a configuration design combines traditional toll collection on the mainline and separate ORT lanes to the side.

Abuzwidah and Abdel-Aty (2017) also evaluated the effect of number and types of toll booths on safety at traditional toll plazas. This study showed that as the number of toll booths increases, crashes are more likely to occur because the number of lane changes increases. Moreover, this study found that as the number of manual toll collection lanes increases, crashes also are more likely to occur.

Chakraborty et al. (2020) assessed the safety impacts of converting Hybrid Toll Plazas to All-Electronic-Toll-Collection (ATEC) system using crash data. Empirical Bayes and Full Bayes methods were utilized in this study. The results indicated that the conversion to the AETC system considerably reduced the number of crashes.

2.2.2. Safety analysis using vehicle trajectories

Although crash data has long been used as a reliable performance measure for road safety, it takes long time to collect sufficient crash data for analysis of safety of toll plaza since crashes are rare events. Thus, some researchers analyzed safety of toll plaza based on the risk of collision predicted using vehicle trajectories collected from video, driving simulator, or traffic simulation.

For instance, Xing et al. (2020a, 2020b) investigated traffic conflicts in the upstream diverging area of toll plaza using trajectory data extracted from unmanned aerial vehicle

(UAV) videos. These studies used the extended time-to-collision (TTC) for the evaluation of collision risk. Logistic regression model, non-parametric models such as K-Nearest Neighbor (KNN), time-varying logistic regression (TLR) model were developed to examine the effects of influencing factors on collision risk over travel time. It was found that the following vehicle's speed, travel distance, initial lane and toll collection type, and the lead vehicle's toll collection type, distance between two vehicles have significant effects on collision risk.

Valdés et al. (2016) evaluated the safety of two configurations of signs at toll plaza as shown in Figure 2-2 based on standard deviation of the average position of 20 subject drivers in the roadway (SDRP), mean speed, and acceleration noise in each of 5 different zones. They concluded that the proposed configuration with overhead sign (Figure 2-2(b)) shows smaller SDRP and mean speed than the current configuration with roadside design (Figure 2-2(a)), which indicates smoother and less frequent lane changes in lower speed and safer driving behaviours.

Jehad et al. (2018) assessed the impact of toll lane configuration on safety using vehicle trajectories from a Vissim microsimulation model. They tested 5 scenarios of different configuration for 10 toll lanes with different toll payment methods – ETC, Radio-frequency identification (RFID) and Touch-N-Go cards payment system. Among different scenarios of toll lane configuration, all ETC lanes showed the lowest number of crossing and lane-changing conflicts. This indicates that all ETC lanes were safer than toll lane configuration with different toll payment methods.

2.3. Surrogate safety measures

As mentioned in previous section, researchers have assessed the safety of toll plaza based on the collision risk predicted using vehicle trajectories collected from video, traffic simulation or driving simulator. Variety of surrogate safety measures have been developed using vehicle trajectories. In this section, common surrogate safety measures used by researchers are described and their benefits and shortcomings are discussed.

2.3.1. Time-to-collision and Time exposed to Time-to-collision

Time-to-collision (TTC) has been used to classify the rear-end conflict between two vehicles in car-following conditions. TTC is the minimum time for the following vehicle to reach the position of the lead vehicle with the initial constant velocity at the time instant when the following vehicle begins braking to avoid the collision with the lead vehicle. TTC can be calculated using the following equation:

$$\mathrm{TTC}(t) = \frac{S_i(t)}{V_i(t) - V_{i-1}(t)}, \quad \text{if } V_i(t) \geq V_{i-1}(t)$$

(1)

where $S_i(t)$ is the spacing between the rear of the lead vehicle i-1 and the front of the following vehicle i at time t, and $V_i(t)$ and $V_{i-1}(t)$ = speed of the following vehicle i and the lead vehicle i-1, respectively, at time t.

Time exposed to TTC (TTE) is defined as the sum of all time intervals when the value of TTC is lower than a specific TTC threshold value (TTC_{th}) as follows:

$$\mathrm{TET} = \frac{1}{T}\sum_{t=0}^{N} \Pr(\mathrm{TTC}(t) < TTC_{th}) \times \Delta t \tag{3}$$

where Δt = the observation time interval, N = the total number of time intervals, and T = the total observation time period ($T = N \times \Delta t$). Thus, shorter TTC and longer TET represent higher risk of rear-end collision. Although TTC and TET have been used widely by previous researchers, it neglects the changes in accelerations of the lead and following vehicles over time.

2.3.2. Deceleration to avoid crashes and Crash Potential Index

Unlike TTC, Deceleration to avoid crashes (DRAC) estimates collision risk based on the assumption that the driver takes evasive action to avoid a collision. DRAC is defined as the minimum required deceleration rate of the following vehicle to safely stop behind the lead vehicle. DRAC can be calculated using the following equation:

$$\mathrm{DRAC}(t) = \frac{(V_{i-1}(t) - V_i(t))^2}{2(X_{i-1}(t) - X_i(t))},\ V_i(t) > V_{i-1}(t) \tag{4}$$

To measure the driver's capability of avoiding a collision by applying brake, Cunto and Saccomanno (2008) developed the Crash Potential Index (CPI). CPI is defined as the probability that DRAC is greater than the maximum available deceleration rate (MADR) of the vehicle. CPI can be calculated using the following equation:

$$\mathrm{CPI} = \frac{1}{T}\sum_{t=0}^{N} \Pr\big(\mathrm{DRAC}(t) > \mathrm{MADR}(t)\big) \times \Delta t \tag{5}$$

where Δt = the observation time interval, N = the total number of time intervals, and T = the total observation time period ($T = N \times \Delta t$).

2.3.3. Aggregate Conflict Propensity Metric (ACPM)

The previous surrogate safety measures only estimate rear-end conflicts and do not consider driver's reaction time. To consider other types of collision (e.g., lane-change conflicts) and driver's reaction time, Wang and Stamatiadis (2013) developed the Aggregate Conflict Propensity Metric (ACPM). ACPM estimates the crash probability for crossing, rear-end and lane-change conflicts. In particular, ACPM assumes that the lane-change conflicts may lead to a sideswipe collision or a rear-end collision. For instance, the Required Braking Rate (RBR) to avoid a sideswipe collision during lane changes ($RBR_{LC\text{-}SS}$) is calculated using the following equation:

$$\mathrm{RBR}_{\mathrm{LC-SS}} = \frac{\frac{2\mathrm{V}_2 \mathrm{l}_1}{\mathrm{V}_1} + \mathrm{l}_2 - \mathrm{l}_1 * \cos\theta - \frac{\mathrm{w}_1}{\sin\theta} - \frac{\mathrm{w}_2}{\tan\theta}}{\left(\mathrm{TTC} + \left(\frac{\mathrm{l}_1}{\mathrm{V}_1}\right) - \mathrm{x}\right)^2} \tag{6}$$

where x = reaction time of driver, V_2 = speed of the trailing vehicle in the target lane, V_1 = speed of the lane-changing vehicle, l_2 = length of the trailing vehicle in the target lane, l_1 = length of the lane-changing vehicle, w_2 = width of the trailing vehicle in the target lane, w_1 = width of the lane changing-vehicle, and θ = conflict angle which is illustrated in Figure 2-5.

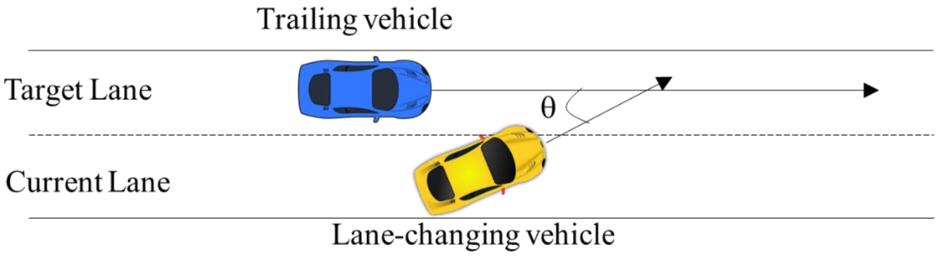


FIGURE 2-5. CONFLICT ANGLE DURING LANE CHANGES

The RBR to avoid a rear-end collision during lane changes ($RBR_{LC\text{-}RE}$) is calculated as follows:

$$\mathrm{RBR}_{\mathrm{LC-RE}} = \frac{(\mathrm{V}_2 - \mathrm{V}_1)^2}{2\left[\mathrm{V}_2 * (\mathrm{TTC} - \mathrm{x}) + \mathrm{V}_1 * \mathrm{x} + \frac{\mathrm{w}_1}{2\sin\theta} + \frac{\mathrm{w}_2}{2\tan\theta} + \frac{(\mathrm{l}_1 * \cos\theta - \mathrm{l}_2)}{2} - \mathrm{l}_1\right]} \tag{7}$$

ACPM predicts that a sideswipe crash will occur if $\mathrm{RBR}_{\mathrm{LC\text{-}SS}}$ is greater than Maximum Available Braking Rate (MABR) of a given vehicle. The model also predicts that a rear-end crash will occur if $\mathrm{RBR}_{\mathrm{LC\text{-}RE}}$ is greater than MABR and $\mathrm{RBR}_{\mathrm{LC\text{-}SS}}$.

ACPM also predicts a real-end collision during car-following condition. The RBR to avoid a rear-end collision during car-following condition ($\mathrm{RBR}_{\mathrm{CF\text{-}RE}}$) is calculated as follows:

$$\mathrm{RBR}_{\mathrm{CF-RE}} = \frac{\mathrm{V}_2 - \mathrm{V}_1}{2 * (\mathrm{TTC} - \mathrm{x})} \tag{8}$$

The predicted conflicts by ACPM were compared with annual crash frequencies by type (crossing, rear-end and lane-change). It was found that they were strongly correlated (Wang and Stamatiadis, 2013). Thus, ACPM is a reliable surrogate safety measure which can accurately predict the number of actual crashes by type.

2.4. Operational Analysis of Toll Plaza

Some studies analyzed the impacts of toll plaza configuration on traffic performance. McKinnon et al. (2014) predicted drivers' decision-making and consequent traffic performance after ETC lanes are added in toll plaza using VISSIM traffic simulation model. The results indicated that toll lanes with multiple forms of toll payment help disperse traffic demand during peak hours. However, accepting both manual and electronic toll collection system degraded the level of service and increased delays for all drivers. Moreover, drivers were sensitive to the slower-moving vehicles and tried to avoid queued heavy vehicles in both cash and ETC lanes.

Bains et al. (2017) also found from VISSIM simulation results that separate lanes for cars and heavy vehicles decreased throughput volume and increased the queue length at toll plaza. Although the separation of heavy vehicles from cars is generally expected to reduce conflicts between different vehicle types and improve traffic performance, this benefit was not observed due to high volume of cars in the studied toll plaza. Moreover, it was found that traffic volumes and types of toll service affected traffic operations of the toll plaza (Hamid, 2011).

3. DATA

3.1. Study area

In this study, advanced toll information system will be developed and tested for the toll plaza at the Gordie Howe International Bridge between Windsor, Ontario and Detroit, Michigan as shown in Figure 3-1. The Gordie Howe International Bridge is a cable-stayed international bridge across the Detroit River and the bridge is currently under construction. The bridge will connect Interstate 75 and Interstate 96 in Michigan with Highway 401 in Ontario through the Rt. Hon. Herb Gray Parkway extension of Highway 401. The bridge will provide uninterrupted freeway traffic flow, as opposed to the current configuration with the nearby Ambassador Bridge which connects to city streets on the Ontario side.

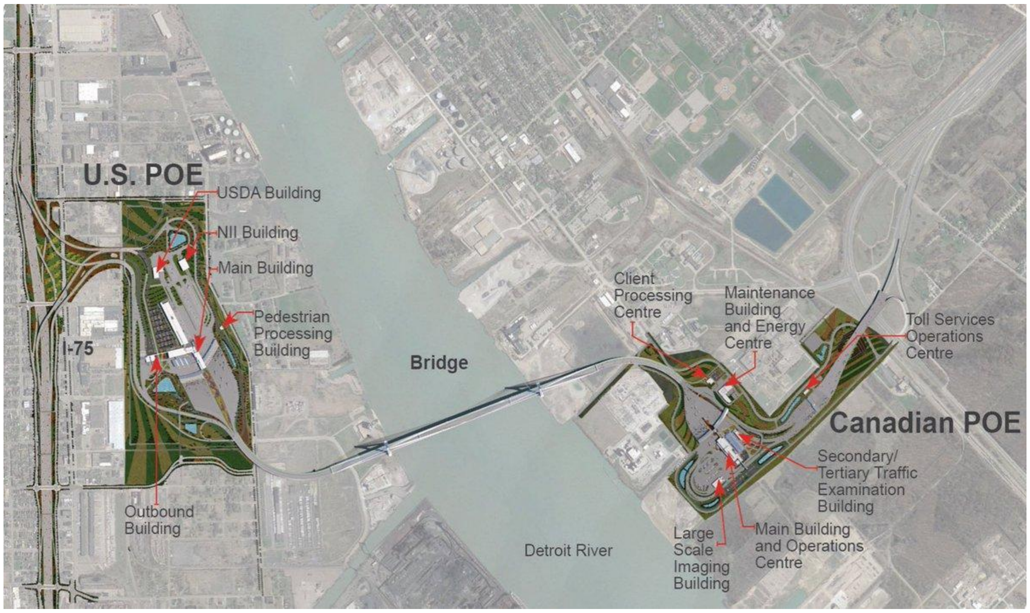


Figure 3-1. Map of Gordie Howe International Bridge (Source: WDBA, 2022)

Based on the annual report (2019-2020) provided by Windsor-Detroit Bridge Authority (WDBA, 2022), Canadian port of entry (POE) in the Gordie Howe International Bridge is a 53-hectare site with total building space of 12,438 m^2. It has toll collection facilities for both Canada- and U.S.-bound traffic and will be the largest Canadian POE along the Canada-U.S. border (WDBA, 2022). The conceptual design of the toll plaza for Canada-bound Gordie Howe International Bridge is shown in Figure 3-2.

FIGURE 3-2. CONCEPTUAL DESIGN OF TOLL PLAZA AT CANADA-BOUND GORDIE HOWE INTERNATIONAL BRIDGE (SOURCE: WDBA, 2022)

Detailed drawings of the design layout of toll plaza for both Canada-bound and U.S.-bound Gordie Howe International Bridge were provided by the WDBA in 2021. The preliminary design plans for the Canada-bound toll plaza proposes that there are 4-lane entry road for passenger cars and 3-lane entry road for heavy vehicles upstream of the toll plaza and these entry roads merge to the toll lane as shown in Figure 3-3. The distance between the merge point and the entry gate of the toll plaza is 160 m. The entry gate is located 75 m upstream of toll booth. The entry gate will be closed only when the toll booth is closed due to low traffic volume. These details are subject to change.

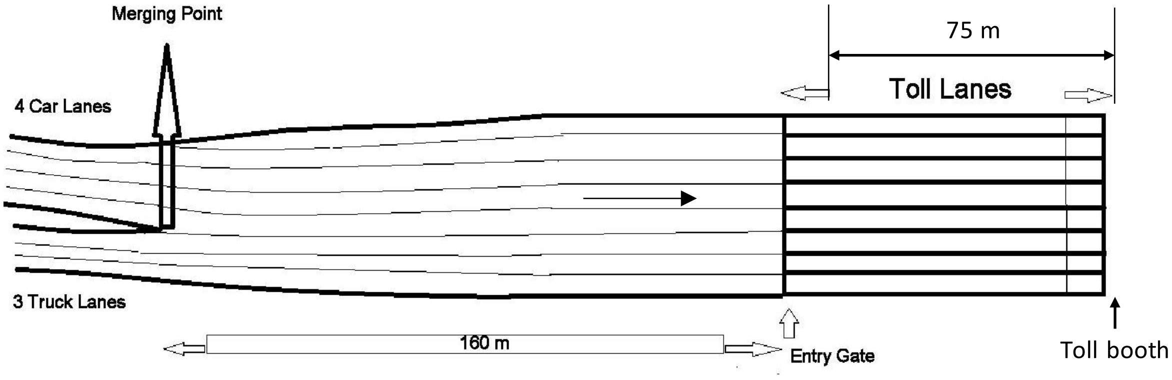


FIGURE 3-3. SCHEMATIC DRAWING OF CANADA-BOUND TOLL PLAZA

According to the WDBA, the following three methods of toll payment will be accepted at the tollbooth: 1) Manual toll collection (MTC) – payment in cash, 2) Electronic toll collection (ETC) – payment with a transponder, and 3) Automatic toll collection (ATC) – non-cash payment without a transponder (e.g., credit card). In case of ETC, as the toll payment is processed via wireless communication between a transponder and toll booth, vehicles can pass through toll booth without reducing the speed or stopping. In each toll lane, only specific toll payment method(s) (e.g., ETC and ATC only) or all toll payments will be accepted.

A proposed lane assignment scenario (subject to change) includes 8 toll lanes with the assigned payment method and type of vehicle at the Canada-bound toll plaza is shown in Figure 3-4. The same lane configuration is also proposed for the U.S.-bound toll plaza. Lane number starts from the innermost lane. Lanes 1-3 are only open to cars whereas Lanes 7-8 are only open to heavy vehicles for all toll payment methods. Lanes 4 and 5 are only open to ETC and ATC for both cars and heavy vehicles where the presence of toll collectors is not required. Only Lane 6 is open to all vehicles with all toll payment methods.

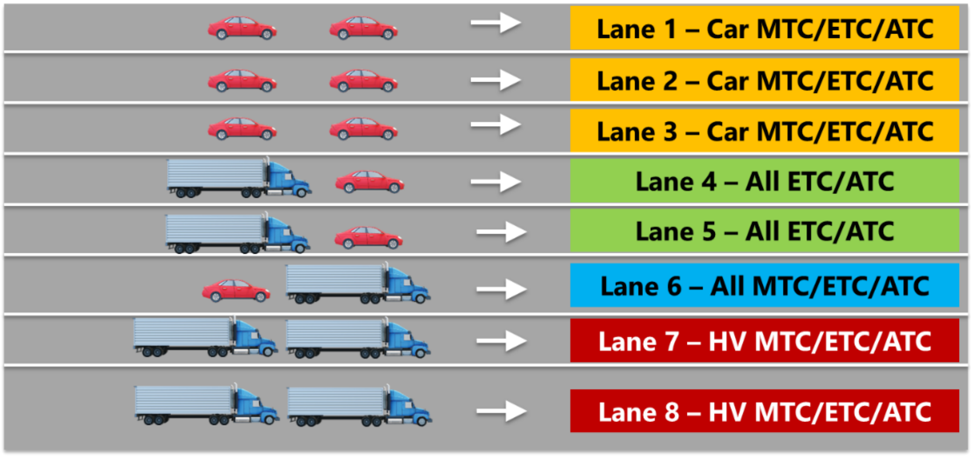


FIGURE 3-4. CONFIGURATION OF TOLL LANES AT CANADA-BOUND TOLL PLAZA

3.2. Travel demand

To estimate the travel demand for the toll plaza, Canada-U.S. cross-border trip tables for the Gordie Howe International Bridge developed in the most recent border crossing origin-destination surveys (WSP, 2018) was used. The survey was conducted by U.S. Federal Highway Administration (FHWA) for passenger cars in 2015 and commercial vehicles in 2012 (WSP, 2018). The growth of international traffic demand and the traffic demand for Gordie Howe International Bridge were forecasted based on regression analysis of a combination of variables such as regional socioeconomic variables.

The Planning Needs and Feasibility (P/N&F) and DRIC Draft EIS (DEIS) models incorporated domestic trip tables from the local models in combination with modified international cross-border trip tables. The trip tables were modified to account for impacts of population and employment changes in addition to regional growth shifts, historical trends, spatial patterns, and factors influencing travel behavior.

It was forecasted that although population and employment would increase by 40% in Wayne County, Michigan from 2005 to 2035, only a small portion of this growth would affect the international travel and the impact on cross-border traffic volumes would be low. Travel demand for the Gordie Howe International Bridge in 2025 and 2040 was forecasted based on 2025 and 2040 daily trip tables compiled by WSP (2018), respectively. Daily travel demand for the Gordie Howe International Bridge was forecasted for passenger cars and commercial vehicles separately as shown in Table 3-1.

Table 3-1. Forecasted Daily Trips for Gordie Howe International Bridge

Year	2025		2040	
Vehicle type Direction	Passinger car	Commercial vehicle	Passenger car	Commercial vehicle
Canada-bound	3159	4201	2882	5570
US-bound	3636	4026	3175	5357

4. METHODS

4.1. VISSIM traffic simulation

As the Gordie Howe International Bridge is currently under construction, there is no observed traffic data for toll plaza on the bridge. Thus, the VISSIM microscopic traffic simulation model (PTV AG, 2022) was used to replicate traffic at the Gordie Howe International Bridge toll plaza with the proposed toll lane configuration as shown in Figure 3-4. The VISSIM model was also used to predict the changes in driver behavior due to the proposed toll information system and assess the impacts of the system on traffic performance and collision risk. Previous studies have used VISSIM traffic simulation to simulate traffic at different roads sections particularly toll plazas. They used real world traffic data to calibrate and validate the simulation (McKinnon et al., 2014; Jehad et al., 2018). The VISSIM model is an effective tool to assess the operation at toll plazas (Bains et al., 2017).

Figure 4-1 shows a VISSIM road network which consists of various links, stop signs at toll booth (red line), the reduced speed areas (yellow rectangles). In the reduced speed areas, vehicles reduce speed to 5 km/h after passing the entry gate and then stop at the toll booth. Peak-hour traffic demand of 300 cars and 300 heavy vehicles was used based on the assumption that 10% of total daily traffic volume (approximately 3,000 cars and 3,000 heavy vehicles per day as shown in Table 3-1) occurs during the peak hour.

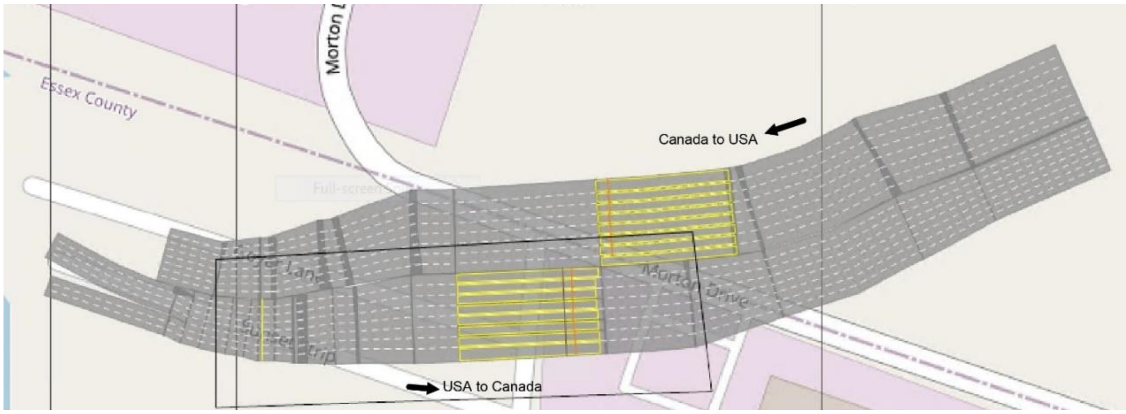


FIGURE 4-1. SCREENSHOT OF ROAD NETWORK OF CANADA-BOUND AND U.S.-BOUND TOLL PLAZA IN VISSIM

Service time is the time during which a vehicle pays toll at the tollbooth and exits from toll plaza, not including the waiting time in the queue. The actual service time depends on the type of toll payment. For instance, the service time for the manual toll collection is generally longer than the automatic toll collection because of longer transaction time for cash payment than card payment. It is also expected that the variability of service time is larger for the manual toll collection than the automatic toll collection because the service time varies with the toll collector's experience (Al-Deek et al., 1997). So, higher standard deviation was assumed for service time of manual payment.

Traffic congestion also affects the service time because when toll collectors are under greater pressure from a growing queue, they tend to process transactions faster (Woo et al., 1991). Thus, the service time for the manual toll collection will be shorter in peak hours than off-peak hours. Also, Al-Deek et al. (1997) found that the service time was relatively longer for heavy vehicles than cars (about 2 seconds) mainly because heavy vehicles accelerate more slowly than cars after toll payment. Based on these factors and our judgment, different service times were assumed for manual and automatic toll collection by car and heavy vehicle as shown in Table 4-1. The distribution of service time was assumed to be normal distribution and the ranges of service time were generated by Vissim.

Table 4-1. Service times of different toll payment methods

Toll payment method	Range	Mean	Standard deviation
Car Manual	0-110 s	10 s	10 s
Car Automatic	0-55 s	5 s	5 s
HV Manual	0-112 s	12 s	10 s
HV Automatic	0-57 s	7 s	5 s

Different proportions of toll payment method were also assumed for cars and heavy vehicles as shown in Table 4-2. For heavy vehicles, significantly higher proportion of electronic toll payment than manual and automatic toll payment was assumed because they are more likely to be equipped with transponders due to the law – heavy vehicles without a valid transponder are charged under the Highway Traffic Act (407 Express Toll Route, 2022). For cars, the same proportions were assumed for the three toll payment methods.

Table 4-2. Proportions of toll payment method by vehicle type

Toll payment method \ Vehicle type	Car	HV
Manual	33%	10%
Automatic	33%	10%
Electronic	33%	80%

Proportions of toll lane use for different toll payment method were assumed for cars and heavy vehicles separately as shown in Table 4-3. It was assumed that cars and heavy vehicles are more likely to use the toll lanes that are exclusively open to cars and heavy vehicles, respectively – Lanes 1, 2 and 3 for cars and Lanes 7 and 8 for heavy vehicles. In case of manual toll payment, this tendency is particularly higher for cars than heavy vehicles because Lane 6 (shared toll lane with heavy vehicles) is far from Lanes 1-3 whereas Lane 6 is adjacent to Lanes 7 and 8. It was also assumed that cars and heavy vehicles are less likely to use Lane 6 because the lane is open to all vehicle types and payment types and it is likely to be the busiest lane.

Table 4-3. Proportions of toll lane use by vehicle type and toll payment method

	Toll Lane							
	Car MTC/ETC/ATC			All ETC/ATC		All	HV MTC/ETC/ATC	
Vehicle Type	1	2	3	4	5	6	7	8
MTC Car	95%			N/A		5%	N/A	
ETC/ATC Car	35%			60%		5%	N/A	
MTC HV	N/A			N/A		30%	70%	
ETC/ATC HV	N/A			40%		10%	50%	

To restrict each vehicle type (i.e., car or heavy vehicle with specific toll payment methods) to use only above designated toll lanes, the vehicle routes for each vehicle type were separately created in VISSIM. In each vehicle route, the "route decision point" was specified as an origin and the designated toll lane was specified as a destination.

To reflect the fact that drivers are more likely to choose the toll lane with shorter queue length to avoid delay, the "queue counter" was placed at each toll booth in VISSIM. This allows drivers to compare the queue length among different toll lanes and choose the lane with the shortest queue length. Although drivers cannot accurately measure the queue length in all lanes and they do not always prefer the shortest queue in real world, it was assumed that drivers have perfect information on the queue length and always choose the lane with the shortest queue length. This assumption made the drivers' lane choice behaviours more deterministic and conservative in VISSIM.

As the real-world driver behaviours at Gordie Howe International Bridge cannot be observed, the existing calibrated VISSIM driving behavior parameters (car-following and lane-changing) in the previous studies were used. In case of car-following parameters, a set of 10 parameters calibrated using the observed vehicle trajectories from the US-101 freeway in California in Durrani et al. (2016) were used as shown in Table 4-4. The description of each parameter is shown in Table 4-5.

Table 4-4. VISSIM Car-following parameters (Source: Durrani et al., 2016)

Model parameters	Unit	Car	Heavy Vehicle
CC0	M	4.15	4.69
CC1	S	1.5	2.7
CC2	M	11.58	14.02
CC3	S	-4	-4.55
CC4	m/s	-1.65	-2.07
CC5	m/s	1.65	2.07
CC6	m/s	11.44	11.44
CC7	m/s^2	0.09	0.1
CC8	m/s^2	0.49	0.27
CC9	m/s^2	0.45	0.25

Table 4-5. Description of VISSIM car-following parameters (Source: PTV AG, 2021)

Parameters	Description
CC0	It's the average desired standstill distance between two vehicles and it has no variation.
CC1	Time distribution of speed-dependent part of desired safety distance Shows number and name of time distribution Each time distribution may be empirical or normal. Each vehicle has an individual, random safety variable which is considered as CC1.
CC2	It restricts the distance difference (longitudinal oscillation) or how much more distance than the desired safety distance a driver allows before he intentionally moves closer to the car in front.
CC3	It controls the start of the deceleration process, i.e. the number of seconds before reaching the safety distance. At this stage the driver recognizes a preceding slower vehicle.
CC4	It defines negative speed difference during the following process. Low values result in a more sensitive driver reaction to the acceleration or deceleration of the preceding vehicle.
CC5	It defines positive speed difference. Enter a positive value for CC5 which corresponds to the negative value of CC4. Low values result in a more sensitive driver reaction to the acceleration or deceleration of the preceding vehicle.
CC6	It's the influence of distance on speed oscillation. For value 0, the speed oscillation is independent of the distance and for the larger value, lead to a greater speed oscillation with increasing distance.
CC7	It's the oscillation during acceleration.
CC8	It's the desired acceleration when starting from standstill (limited by maximum acceleration defined within the acceleration curves).
CC9	It's the desired acceleration at 80 km/h (limited by maximum acceleration defined within the acceleration curves).

In case of lane-changing parameters, a set of 9 calibrated parameters reported in CDM Smith (2014) was used as shown in Table 4-6. The description of each lane-changing parameter is shown in Table 4-7.

Table 4-6. VISSIM lane-changing parameters (Source: CDM Smith, 2014)

	Unit	Lane-change vehicle	Trailing vehicle in the target lane
Maximum deceleration	ft/sec^2	-10	-8
-1 ft/sec^2 per distance	Ft	100	100
Accepted deceleration	ft/sec^2	-3.28	-3.28
Waiting time before diffusion	Sec	60	
Minimum front-to-rear headway	Ft	1.64	
Safety distance reduction factor	-	0.65	

Table 4-7. Description of VISSIM lane-changing parameters (Source: PTV AG, 2021)

Parameters	Description
Maximum Deceleration	It's the maximum deceleration for changing lanes based on the specified routes for own vehicle overtaking and the trailing vehicle.
Cooperative Lane changing	If vehicle A observes that a leading vehicle B on the adjacent lane wants to change to his lane A, then vehicle A will try to change lanes itself to the next lane in order to facilitate lane changing for vehicle B.
Front-to-rear headway	It's the minimum distance between two vehicles that must be available after a lane change, so that the change can take place (default value 0.5 m). A lane change during normal traffic flow might require a greater minimum distance between vehicles in order to maintain the speed-dependent safety distance.
Safety distance reduction factor	This parameter concerns the safety distance of the trailing vehicle on the new lane for determining whether a lane change will be carried out, the safety distance of the lane changer itself and the distance to the preceding, slower lane changer. During the lane change, Vissim reduces the safety distance to the value that results from the following multiplication: *Original safety distance * safety distance reduction factor* The default value of 0.6 reduces the safety distance by 40%. Once a lane change is completed, the original safety distance is taken into account again.
Waiting time before diffusion	This period of time is defined as the time a car sits waiting for a gap to change lanes in order to stay on its route before it is removed from the network.

4.2. Simulation scenarios

To determine candidate locations of toll information system, it is important to ensure that drivers have enough time to decide which tollbooth or toll lane they want to use after they see messages and before they arrive the tollbooth (Saad et al., 2019). Considering drivers' workload for comprehending information and making decisions, it is recommended that the toll information system be located within half-mile (805 m) before the toll plaza (Valdés et al., 2016).

It's expected that VMS improves safety and performance of the toll plaza as it helps drivers make earlier decision to choose the toll booth with specific toll payment methods and re-routing vehicles with specific toll payment methods to their designated toll booth in advance. However, in this study, different scenarios were tested to investigate and compare the effects of toll information system with the numerical results in the following three experiments:

In Experiment 1, the impacts of presence and location of VMS (i.e., toll information system) for the current peak-hour traffic demand and toll lane configuration were assessed. VMS displays the information on toll lane configuration as shown in Figure 4-2. Although the provision of toll information in advance will generally help drivers make decisions earlier, VMS must not be too far from the tollbooth due to the limit in driver memory retention. Hanowski and Kantowitz (1997) reported that presenting the information too early increases the chances that drivers forget the information. In particular, older drivers had poorer memory retention 50 seconds after the message disappeared in the in-vehicle information system (IVIS) than immediately after the message disappeared in the IVIS (Hanowski and Kantowitz, 1997).

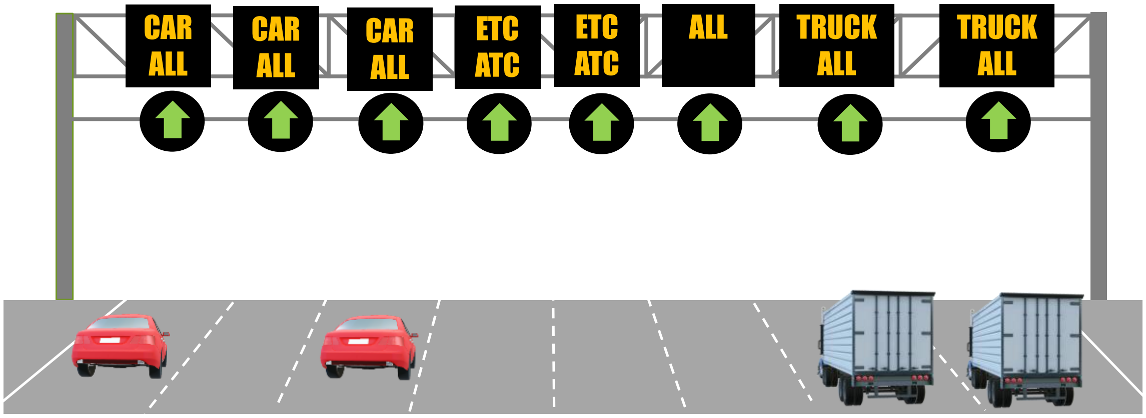
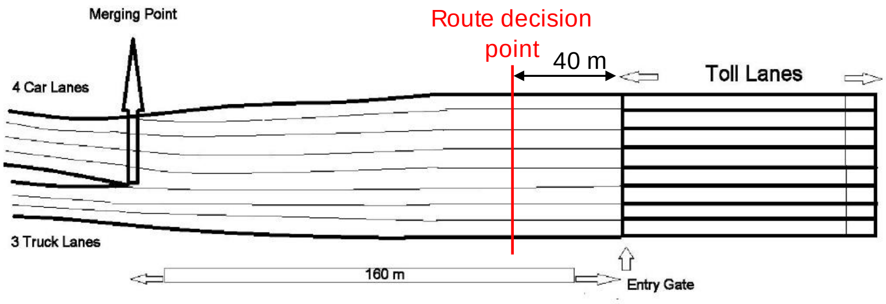
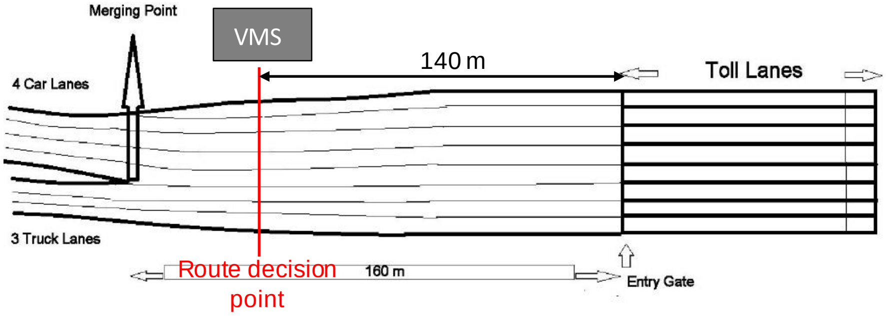


FIGURE 4-2. EXAMPLE OF VARIABLE MESSAGE SIGNS LOCATED UPSTREAM OF TOLL PLAZA

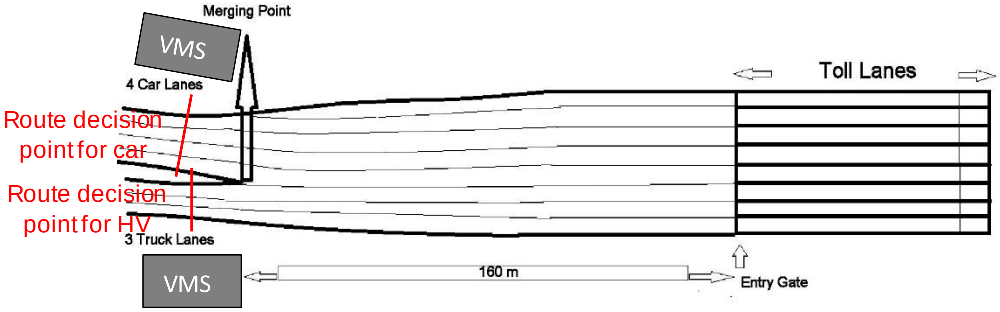
To evaluate the impacts of presence and location of VMS on traffic, three scenarios (no VMS, VMS 140 m from the entry gate, and separate VMS for cars and HVs 75 m before the merge point) were compared as shown in Figure 4-3. The purpose of this comparison is to assess whether placing the VMS further upstream of the toll plaza and providing toll information in more advance can reduce the delay and improve safety of the toll plaza more effectively or not. In case of no VMS, it was assumed that drivers can only see the toll lane sign (e.g., Car All Payment) in each toll booth and select the toll lane 40 m before the entry gate. To reflect driver reactions to VMS in different locations, the location of "route decision points" will be changed in different scenarios in VISSIM.



(a) Scenario 1-1 (Base case – No VMS)



(b) Scenario 1-2 (VMS 140 m before the entry gate)



(c) Scenario 1-3 (Separate VMS for cars and HVs 75 m before the merge point)

FIGURE 4-3. SCENARIOS OF PRESENCE AND LOCATION OF VARIABLE MESSAGE SIGNS IN EXPERIMENT 1

Based on the result of Experiment 1, the impacts of different toll lane configuration for current traffic demand and different percentages of HV were assessed in Experiments 2 and 3. Different toll lane configuration was considered because of potential safety problems with the current proposed toll lane configuration. For instance, as Lane 6 is opened to both cars and HVs with all toll payment methods, it may increase the conflicts between cars and HVs. Also, Lanes 4 and 5 are opened to both ETC and ATC vehicles although ETC vehicles are not required to stop unlike ATC vehicles. Moreover, ATC vehicles are not likely to use the innermost and outermost toll lanes (Lanes 1 and 8, respectively) because many lanes near the center of the road are opened to ATC vehicles. Thus, in Experiment 2, the following two alternative toll lane configurations – 1) convert Lanes 4 to 6 to ETC-only lanes and 2) convert Lanes 1 and 8 to MTC/ETC-only lanes - were compared with the best scenario in Experiment 1 (Base case).

In Experiment 3, the impact of converting Lane 6 to a HV-only lane was assessed for two different percentages of HV (60% and 70%) which are higher than the current percentage of HV (50%). Higher percentage of HV was considered because the number of HVs on the bridge is expected to increase faster than cars by the year 2040 according to the forecasted travel demand provided by WSP (2018) as shown in Table 3-1.

The results from the above scenarios were compared in terms of delay, collision risk, number of lane changes and queue length. Individual vehicle trajectories from VISSIM model were used to determine collision risk and number of lane changes. As rear-end and lane-change crashes are dominant types of crashes at toll plaza, rear-end and lane-change collision risk were estimated using various surrogate safety measures as discussed in Chapter 2.3.

5. RESULTS AND DISCUSSION

In this chapter, VISSIM simulation was run for the two experiments. For each experiment, the averages of the values from 5 simulation runs were calculated for each scenario. The results for two experiments have been presented and discussed in the next sections.

5.1 Experiment 1 – Impacts of presence and location of toll information system

In Experiment 1, the impacts of presence and location of VMS on delay and safety was assessed. Three scenarios - 1-1: no VMS, 1-2: VMS 140 m from the entry gate, and 1-3: VMS before the merge point – were compared.

5.1.1 Average number of vehicles

The average numbers of cars and trucks with various payment methods in the entire network were calculated and compared among the three scenarios as shown in Tables 5-1. The average numbers of vehicles for different vehicle types were similar in all scenarios.

Table 5-1. Average number of vehicles by vehicle type and toll payment method in Experiment 1

Scenario / Vehicle type	1-1 (No VMS)	1-2 (VMS 140 m before the entry gate)	1-3 (VMS before the merge point)
Car MTC	101.8	101.0	100.0
Car ETC	104.8	105.2	104.8
Car ATC	102.0	100.8	101.0
HV MTC	32.6	32.8	32.8
HV ATC	29.0	28.4	28.6
HV ETC	236.2	235.8	235.0
Total	606.4	604.0	602.2

The average number and percentage of exit vehicles at each toll booth are shown in Table 5-2. The average number and percentage of exit vehicles for each toll booth was generally similar in all scenarios except for the lanes that are used by only cars (Lanes 1, 2 and 3). Cars were distributed more evenly across Lanes 1 to 3 in Scenario 1-3 than Scenarios 1-1 and 1-2. Table 5-3 also shows the average number and percentage of exit vehicles by vehicle type.

Table 5-2. Average number and percentage of exit vehicles by toll booth in Experiment 1

Toll booth	1-1 (No VMS)		1-2 (VMS 140 m before the entry gate)		1-3 (VMS before the merge point)	
Lane 1 – Car MTC/ETC/ATC	42.8	7.1%	45.0	7.5%	**30.8**	5.1%
Lane 2 – Car MTC/ETC/ATC	25.2	4.2%	20.2	3.4%	**51.4**	8.5%
Lane 3 – Car MTC/ETC/ATC	102.2	16.9%	103.8	17.3%	**84.6**	14.1%
Lane 4 – All ETC/ATC	114.0	18.7%	114.2	18.8%	123.8	20.6%
Lane 5 – All ETC/ATC	117.6	19.4%	116.8	19.3%	107.8	17.9%
Lane 6 – All MTC/ETC/ATC	50.2	8.3%	51.2	8.5%	51.2	8.5%
Lane 7 – HV MTC/ETC/ATC	81.0	13.3%	78.2	12.9%	78.4	13.0%
Lane 8 – HV MTC/ETC/ATC	73.4	12.1%	74.6	12.3%	74.2	12.3%

Table 5-3. Average number and percentage of exit vehicles by vehicle type and toll booth in Experiment 1

Toll booth	Vehicle type	1-1 (No VMS)		1-2 (VMS 140 m before the entry gate)		1-3 (VMS before the merge point)	
Lane 1	Car MTC	23	22.8%	23.2	23%	**11.4**	11.4%
	Car ETC	9.8	9.6%	12	11.3%	11	10.6%
	Car ATC	10	9.8%	9.8	9.8%	8.4	8.4%
Lane 2	Car MTC	13	12.7%	10.2	10%	**30.4**	30.5%
	Car ETC	7.2	6.8%	5.6	5.5%	12.6	12%
	Car ATC	5	4.9%	4.4	4.4%	8.4	8.4%
Lane 3	Car MTC	61	59.8%	62.8	62.1%	53.4	53.2%
	Car ETC	22.6	21.7%	22	21.1%	15.4	14.8%
	Car ATC	18.6	18.4%	19	18.9%	15.8	15.7%
Lane 4	Car ETC	43.8	41.5%	43.4	40.8%	50.6	48%
	Car ATC	43.6	42.5%	42.6	42%	49.8	49.1%
	HV ATC	3	9.8%	2.8	9.8%	2	6.7%
	HV ETC	23.6	10%	25.4	10.8%	21.4	9.2%

Table 5-3. Average number and percentage of exit vehicles by vehicle type, toll payment method and toll booth in Experiment 1 (Continued)

Toll booth	Vehicle type	1-1 (No VMS)		1-2 (VMS 140 m before the entry gate)		1-3 (VMS before the merge point)	
Lane 5	Car ETC	16.8	15.9%	17.6	16.7%	10.6	10%
	Car ATC	20.2	19.9%	20.4	20.3%	14	13.8%
	HV ATC	6.6	22.4%	6.4	21.7%	7.4	25.5%
	HV ETC	74	31.5%	72.4	30.7%	75.8	32.2%
Lane 6	Car MTC	4.8	4.7%	4.8	4.7%	4.8	4.8%
	Car ETC	4.6	4.4%	4.6	4.4%	4.6	4.4%
	Car ATC	4.6	4.5%	4.6	4.5%	4.6	4.5%
	HV MTC	8.4	26.6%	9.2	29%	9.2	29%
	HV ATC	4	13.7%	4	14%	4	13.9%
	HV ETC	23.8	9.9%	24	10%	24	10%
Lane 7	HV MTC	11	33.5%	10	29.9%	9.4	28.5%
	HV ATC	7.4	26.1%	6.8	24.5%	6.4	23.1%
	HV ETC	62.6	26.5%	61.4	26%	62.6	26.6%
Lane 8	HV MTC	13.2	39.8%	13.6	41%	14.2	42.5%
	HV ATC	8	27.9%	8.4	29.8%	8.8	30.7%
	HV ETC	52.2	22.1%	52.6	22.4%	51.2	21.8%

Figure 5-1 compares the percentage of exit vehicles by vehicle type, toll payment method and toll booth. The figure shows that the percentages of toll lane use for each vehicle type were different among the three scenarios. For instance, the percentages of cars were more similar among Lanes 1, 2 and 3 (car-only lanes) in Scenario 1-3 compared to Scenarios 1-1 and 1-2. This indicates that the VMS upstream of the merge area helped car drivers make earlier decision to choose the toll booth in car-only lanes. However, the percentages of cars with ETC and ATC were relatively higher for Lane 4 than Lane 5 in Scenario 1-3. On the other hand, the percentages of heavy vehicles in different lanes were generally similar among the three scenarios.

FIGURE 5-1. AVERAGE PERCENTAGE OF EXIT VEHICLES BY VEHICLE TYPE, TOLL PAYMENT METHOD AND TOLL BOOTH IN EXPERIMENT 1

5.1.2 Delay and queue length

Average delay for the entire road network was compared among the three scenarios as shown in Table 5-4. The table shows that the average delay for all vehicles was slightly lower for Scenario 1-3 than the other 2 scenarios and Scenario 1-2 had highest delay. This indicates that VMS before the merge area is more effective in re-routing vehicles with specific toll payment methods to their designated toll booth in advance.

Table 5-4. Comparison of average delay per vehicle (seconds) in Experiment 1

Scenarios	All	Car MTC	Car ATC	Car ETC	HV MTC	HV ATC	HV ETC
1-1	24.3	35.2	15.3	10.4	47.2	18.4	17
1-2	25.7	19.9	15.0	16.5	44.7	28	29.3
1-3	23.6	33.4	14.9	10.9	45.4	18.2	17

Average queue length and maximum queue length for the entire road network were compared among the three scenarios as shown in Table 5-5. The table shows that Scenario 1-3 had the shorter queue length than the other two scenarios, which resulted in lower delay as shown in Table 5-4. The table also shows that all ETC/ATC lanes had the longest queue length and all MTC/ETC/ATC lanes had the shortest queue length in all three scenarios. This is due to higher demand for all ETC/ATC lanes (Lanes 4 and 5) and lower demand for all MTC/ETC/ATC lane (Lane 6) as shown in Table 5-2.

Table 5-5. Comparison of queue length in Experiment 1

	Scenario 1-1		Scenario 1-2		Scenario 1-3	
Toll lanes	Average queue length	Maximum queue length	Average queue length	Maximum queue length	Average queue length	Maximum queue length
Car MTC/ETC/ATC lanes (Lanes 1,2,3)	14.3	94.8	16.8	103.5	12.9	81.7
All ETC/ATC lanes (Lanes 4,5)	35.0	108.7	35.2	119.3	31.9	100.7
All MTC/ETC/ATC lanes (Lane 6)	7.0	93.5	8.2	96.1	6.2	71.8
HV MTC/ETC/ATC lanes (Lanes 7,8)	27.4	113.6	27.1	112.9	24.1	101.4

5.1.3 Rear-end collision risk

Average time-to-collision (TTC) for all vehicle types before the entry gate was also compared among the three scenarios. It was found that the average TTC for all lanes was slightly longer for Scenario 1-2 (14.8 s) than Scenario 1-3 (14.6 s) as shown in Table 5-6 (a) and Scenario 1-1 had lowest average TTC (12.4 s). This shows that VMS upstream of the toll booth can reduce rear-end collision risk at the toll plaza. The table also shows that the average values of TTC for lane 1 (Car MTC/ETC/ATC) were relatively low in all three scenarios. However, the average TTC for lane 1 was slightly longer for Scenario 1-3 than the other two scenarios.

Table 5-6. Average TTC (seconds) before the entry gate in Experiment 1

(a) Average TTC by toll booth

Toll booth	Scenario 1-1	Scenario 1-2	Scenario 1-3
Lane 1	6.6	6.1	7.9
Lane 2	13.5	12.8	9.4
Lane 3	9.4	14.9	13.9
Lane 4	11.5	12.9	13.7
Lane 5	12.5	12.9	14.8
Lane 6	14.3	18.2	23.6
Lane 7	15.8	23.4	20.9
Lane 8	13.4	12.2	10.7
Average	**12.4**	**14.8**	**14.6**

(b) Average TTC by type of lead and following vehicles

Following vehicle-Lead vehicle	Scenario 1-1	Scenario 1-2	Scenario 1-3
Car-Car	11.6	16.88	14.5
HV-Car	**25.4**	**20.98**	**39.8**
HV-HV	16.04	17.24	21.5
Car-HV	**13.3**	**18.15**	**31.5**

According to Table 5-6(a), VMS in Scenario 1-2 and Scenario 1-3 can reduce rear-end collision risk (i.e., longer average TTC) in most lanes (lanes 3, 4, 5, 6 and 7). For lanes 2 and 8, VMS rather increased rear-end collision risk.

Moreover, the average values of TTC before the entry gate were also compared among the following 4 types of lead vehicle and following vehicle pair in the same lane: 1) Car-Car: a car following a car, 2) HV-Car: a HV following a car, 3) Car-HV: a car following a HV, and 4) HV-HV: a HV following a HV as shown in Table 5-6(b). The conflicts between car and HV (Car-HV or HV-Car) are considered as more severe conflicts because the impact of collision between vehicles with different sizes and weights on vehicle body is generally higher. In particular, HV-Car is more severe than Car-HV because cars are more likely to be severely damaged when they are hit by HV in the rear.

Table 5-6(b) shows that Scenario 1-3 had higher average TTC for the conflicts between Cars and HVs than Scenarios 1-1 and 1-2. Thus, separate VMS for cars and HVs before the merge point are effective in reducing rear-end collision risk for more severe conflicts.

The duration of time when TTC was less than the threshold of TTC (Time Exposed Time to collision (TET)) upstream of the toll booth was also compared among the three scenarios. Sayed et al. (1994) found that the threshold values of TTC for the low and high levels of conflict are 2 seconds and 0.9 seconds, respectively. Thus, the threshold value of TTC was assumed to be 1.5 seconds as an average based on this study. It was found that TET was lowest for Scenario 1-1 (10623) and highest for Scenario 1-3 (11458). Also, TET was 11346 for Scenario 1-2. This indicates that although VMS significantly increased the average TTC, it also increased the frequency of safety critical events, particularly in Scenario 1-3.

The Required Braking Rates (RBR) to avoid collision in Aggregate Conflict Propensity Metric (ACPM) developed by Wang and Stamatiadis (2013) were also used to estimate rear-end collision risk in car-following condition using the trajectory data extracted from VISSIM. The equations of RBR are provided in Chapter 2.3.3. It should be noted that the RBR for rear-end conflicts in car-following condition (RBR_{CF-RE}) is modified from Deceleration to avoid crash (DRAC) by incorporating the reaction time of driver. The driver’s reaction time was assumed to be 2 seconds. Since the TTC must be longer than 2 seconds according to the equation, the TTCs less than 2 seconds were removed. Table 5-7 shows the VMS increased rear-end collision risk before the toll booth and before the entry gate.

Table 5-7. Average required braking rates (m/s^2) for rear-end conflicts in car following condition in Experiment 1

	Scenario 1-1	Scenario 1-2	Scenario 1-3
Average RBR (before the toll booth)	2.8	3.8	4.0
Average RBR (before the entry gate)	1.2	1.6	1.6

As the ACPM results weren't realistic, the DRAC for the three scenarios in the first experiment before the toll booths was also measured to overcome the shortcoming of ACPM. The average DRAC was 0.424 m/s^2 in Scenarios 1-1 and 0.432 m/s^2 in Scenario 1-2 and 0.443 m/s^2 in Scenario 1-3. According to the results VMS slightly increases DRAC, however the difference among the values of DRAC in the three scenarios wasn't significant.

5.1.4. Number of lane changes

The total number of lane changes upstream of the toll booth was compared among the three scenarios. The total number of lane changes was highest for Scenario 1-1 (693.2) and lowest for Scenario 1-2 (660.6) followed by Scenario 1-3 (665.2) as shown in Table 5-8. In Scenarios 1-2 and 1-3, it was observed that vehicles changed lanes more frequently upstream of the toll booth rather than near the toll booth because vehicles could make route decision in advance at the location of VMS.

The number of lane changes from each origin lane (i.e., the lane where the lane change started) was also compared as shown in Table 5-8. For instance, it was found that the number of lane changes was lower from Lanes 3, 5, 6, 7 and 8 in Scenario 1-2 than Scenario 1-1. Thus, it appears that earlier route decision of vehicles due to VMS helped avoid frequent lane changes near the toll booth.

Table 5-8. Total number of lane changes by origin lane and direction of lane change

Origin lane- direction of lane change	Scenario 1-1	Scenario 1-2	Scenario 1-3
Lane 1- right lane change	32.2	33.6	33.6
Lane 2- right lane change	32.2	33.4	**70.4**
Lane 2- left lane change	1	0.2	1.2
Lane 2- total	33.2	33.6	71.6
Lane 3- right lane change	67.6	65.8	**107**
Lane 3- left lane change	27	21.2	10.4
Lane 3- total	94.6	87	117.4
Lane 4- right lane change	25.8	28.6	41.4
Lane 4- left lane change	83.4	85.8	**51.2**
Lane 4- total	109.2	114.4	92.6
Lane 5- right lane change	16.6	12	14
Lane 5- left lane change	76.2	79.4	**26**
Lane 5- total	92.8	91.4	40
Lane 6- right lane change	50.2	45.2	46.4
Lane 6- left lane change	108.4	106	105.8
Lane 6- total	158.6	151.2	152.2
Lane 7- right lane change	23.6	16	15.8
Lane 7- left lane change	95.6	83	89
Lane 7- total	119.2	99	104.8
Lane 8- left lane change	53.4	50.4	53
Total	693.2	660.6	665.2

In general, the number of lane changes from each origin lane was similar in all three scenarios except for Lanes 2, 3, 4 and 5 in Scenario 1-3. Lanes 2 and 3 had much higher number of right lane changes in Scenario 1-3 compared to Scenarios 1-1 and 1-2. In contrary, Lanes 4 and 5 had much lower number of left lane changes in Scenario 1-3 compared to Scenarios 1-1 and 1-2. Higher number of lane changes is expected to cause higher delay. However, in this case, the queue length for all lanes was lower in Scenario 1-3 than the other two scenarios. Thus, this indicates that higher number of lane changes from some origin lanes rather helped re-routing of cars to their designated toll booth in advance and resulted in more even distribution of vehicles across lanes.

5.1.5 Lane-change collision risk

The Required Braking Rates (RBR) for lane-change collision risk was also estimated using the ACPM method developed by Wang and Stamatiadis (2013). RBR were estimated for sideswipe collision risk and rear-end collision risk during lane changes. The equations of RBR are provided in Chapter 2.3.3. The conflict angle was assumed to be 45 degree and the reaction time of driver was assumed to be 2 seconds. The length and width of cars were assumed to be 4 meters and 2 meters, respectively and the length and width of HVs are assumed to be 10 meters and 2.5 meters, respectively.

Table 5-9 shows that average values of RBR for rear-end conflicts and sideswipe conflicts during lane changes in Scenarios 1-2 and 1-3 were lower than average RBR in Scenario 1-1. Besides RBR, the average number of conflicts in each scenario was also measured as shown in Table 5-9. The conflict was defined as the event when RBR for each lane change is greater than maximum available braking rate (MABR) of 2.4 m/s^2 (= 8 ft/s^2) (CDM Smith, 2014). Although the average number of conflicts in all the three scenarios was very low (about one to two conflicts), the average numbers of sideswipe and rear-end conflicts were lowest in Scenario 1-3. Thus, VMS in Scenarios 1-2 and 1-3 did not only reduce rear-end collision risk, but also lane-change collision risk.

Table 5-9. Average required braking rates (RBR) (m/s^2) and number of conflicts during lane changes in Experiment 1

	Scenario 1-1	Scenario 1-2	Scenario 1-3
Average RBR (sideswipe)	0.38	0.25	0.34
No. of sideswipe conflicts	2.2	2	0.6
Average RBR (rear-end)	0.45	0.22	0.19
No. of rear-end conflicts	1.2	1.2	0.6

The numbers of sideswipe and rear-end conflicts during lane changes were also separately compared for the following 4 types of lane-changing vehicle and trailing vehicle in the target lane: 1) Car-Car: lane-changing car and trailing car, 2) Car-HV: lane-changing car and trailing HV, 3) HV-Car: lane-changing HV and trailing car, and 4) HV-HV: lane-changing HV and trailing HV as shown in Tables 5-10 and 5-11. As it was mentioned before, the conflicts between car and HV (Car-HV or HV-Car) are considered as the more severe conflicts because the impact of collision between vehicles with different sizes and weights on vehicle body is generally higher. In particular, Car-HV is more severe than HV-Car because cars are more likely to be severely damaged when they are hit by HV in the rear.

Table 5-10. Average required braking rates (m/s^2) by type of lane-changing and trailing vehicles for sideswipe conflicts during lane changes in Experiment 1

$RBR_{LC\text{-}SS}$	Scenario 1-1	Scenario 1-2	Scenario 1-3
Car-Car	0.24	0.21	0.26
Car-HV	**0.64**	**0.53**	**0.56**
HV-HV	0.47	0.26	0.40
HV-Car	**0.64**	**0.22**	**0.48**

Table 5-11. Average required braking rates (m/s^2) by type of lane-changing and trailing vehicles for rear-end conflicts during lane changes in Experiment 1

$RBR_{LC\text{-}RE}$	Scenario 1-1	Scenario 1-2	Scenario 1-3
Car-Car	0.23	0.14	0.27
Car-HV	**0.44**	**0.29**	**0.21**
HV-HV	0.26	0.28	0.24
HV-Car	**1.73**	**0.19**	**0.34**

It was found that Scenarios 1-2 and 1-3 generally show lower RBR for both sideswipe and rear-end conflict during lane changes than Scenario 1-1 for all vehicle types except

Car-Car. This is mainly because the total number of lane changes was lower for Scenarios 1-2 and 1-3 than Scenario 1-1 as shown in Table 5-8. As the number of lane changes increases, the risk of lane-change collision also increases. In particular, Scenarios 1-2 and 1-3 showed much lower RBRs for Car-HV and HV-Car. Thus, VMS is more effective in reducing the number of severe conflicts.

It should be noted that the ACPM method only considers the lane change events when the lane-changing vehicle has lower speed than the trailing vehicle in the target lane. Thus, VMS in Scenarios 1-2 and 1-3 decreased the number of lane changes when the speed of lane-changing vehicle was lower than the speed of trailing vehicle in the target lane, which increases collision risk.

In summary, Scenario 1-3 showed benefits in both traffic performance and safety (i.e., lower delay and lower risk of rear-end and lane-change collisions than Scenario 1-1) unlike Scenario 1-2. Thus, it is recommended to locate separate VMS for cars and HVs before the merge area (Scenario 1-3).

5.2 Experiment 2 – Impacts of new toll lane configuration for current traffic demand

5.2.1. Description of scenarios

In Experiment 2, the impacts of different toll lane configuration for current traffic demand were assessed. Since Scenario 1-3 (separate VMS for cars and heavy vehicles before the merge area) was the best scenario in Experiment 1, it was selected as the Base case in Experiment 2. Thus, the performance of the toll information system for different toll lane configurations was assessed in this experiment. The following scenarios were developed and compared with the Base case:

The following two different lane configurations were designed and compared with the Base case:

Scenario 2-1: Convert Lanes 4 to 6 to ETC-only lanes

In this case, Lanes 4 to 6 were designed as ETC-only lanes, Lanes 1 to 3 be designated as car MTC/ATC/ETC lanes and Lanes 7 and 8 be designated as HV MTC/ATC/ETC lanes. So, if the vehicles with ETC increases, they would not have to stop at the toll booth and they can pass through the toll plaza without having to wait behind the lead vehicle with MTC or ATC. This is particularly effective in reducing the delay for the vehicles with ETC because they can pass through the toll plaza without stopping if they use ETC-only lanes. Proportions of toll lane use for different toll payment method were also assumed for cars and heavy vehicles separately as shown in Table 5-12.

Table 5-12. Proportions of toll lane use by vehicle type and toll payment method for Scenario 2-1 (Convert Lanes 4 to 6 to ETC-only lanes)

	Toll Lane							
	Car MTC/ETC/ATC			All ETC			HV MTC/ETC/ATC	
Vehicle Type	1	2	3	4	5	6	7	8
MTC/ATC Car	100%			N/A		N/A	N/A	
ETC Car	30%			70%			N/A	
MTC/ATC HV	N/A			N/A		N/A	100%	
ETC HV	N/A			80%			20%	

Scenario 2-2: Convert Lanes 1 and 8 to MTC/ETC-only lanes

In this scenario, Lanes 1 and 8 were designed as MTC/ETC-only lanes as there are many ATC lanes and the traffic demand for the vehicles with ATC is not much high compared to the vehicles with ETC. Thus, if the vehicle with ETC increases, ATC for Lanes 1 and Lane 8 can be removed. These lanes were not designed as ETC-only lanes because there are not many lanes assigned to the vehicles with MTC. Proportions of toll lane use for different toll payment method were assumed for cars and heavy vehicles separately as shown in Table 5-13.

Table 5-13. Proportions of toll lane use by vehicle type and toll payment method for Scenario 2-2 (Convert Lanes 1 and 8 to MTC/ETC-only lanes)

	Toll Lane							
	Car MTC/ETC	Car MTC/ETC/ATC		All ETC/ATC		All	HV MTC/ETC/ATC	HV MTC/ETC
Vehicle Type	1	2	3	4	5	6	7	8
MTC Car	35%	55%		N/A		10%	N/A	N/A
ATC Car	N/A	35%		60%		5%	N/A	N/A
ETC Car	25%	35%		30%		10%	N/A	N/A
MTC HV	N/A	N/A		N/A		30%	30%	40%
ATC HV	N/A	N/A		55%		10%	35%	N/A
ETC HV	N/A	N/A		40%		10%	20%	30%

5.2.2 Comparison among different toll lane configurations

The average number and percentage of exit vehicles at each toll booth are shown in Table 5-14. As shown in Table 5-2, cars were distributed more evenly across Lanes 1 to 3 in Base case (Scenario 1-3) in the Experiment 1. However, cars were not evenly distributed across Lanes 1 to 3 in Scenario 2-1 as shown in Table 5-14.

Table 5-14. Average number and percentage of exit vehicles by toll booth in Experiment 2

Toll booth	Base case (Scenario 1-3)		Scenario 2-1 (Convert Lanes 4 to 6 to ETC-only lanes)		Scenario 2-2 (Convert Lanes 1 and 8 to MTC/ETC lanes)	
Lane 1	30.8	5.1%	8.8	1.4%	60.6	10%
Lane 2	51.4	8.5%	85	14.1%	54.2	8.9%
Lane 3	84.6	14.1%	**143**	23.6%	71.8	11.9%
Lane 4	123.8	20.6%	74.8	12.4%	102.8	17%
Lane 5	107.8	17.9%	100.2	16.6%	96.6	16%
Lane 6	51.2	8.5%	**88.8**	14.7%	65.4	10.8%
Lane 7	78.4	13.0%	47.2	7.8%	77	12.7%
Lane 8	74.2	12.3%	56	9.3%	71.8	11.9%

Figure 5-2 compares the percentage of exit vehicles by vehicle type, toll payment method and toll booth. The figure shows that the percentages of toll lane use for each vehicle type were different among the three scenarios. For instance, ETC Cars and HVs in Scenario 2-1 were evenly distributed among Lanes 4 to 6 and they used these Lanes more than other shared lanes compared to the other two Scenarios. Moreover, the percentages of MTC and ATC Cars were higher in Lanes 1 to 3 and the percentages of MTC and ATC HVs were higher in Lanes 7 and 8 in Scenario 2-1 than other two scenarios as these vehicles couldn’t use Lanes 4 to 6.

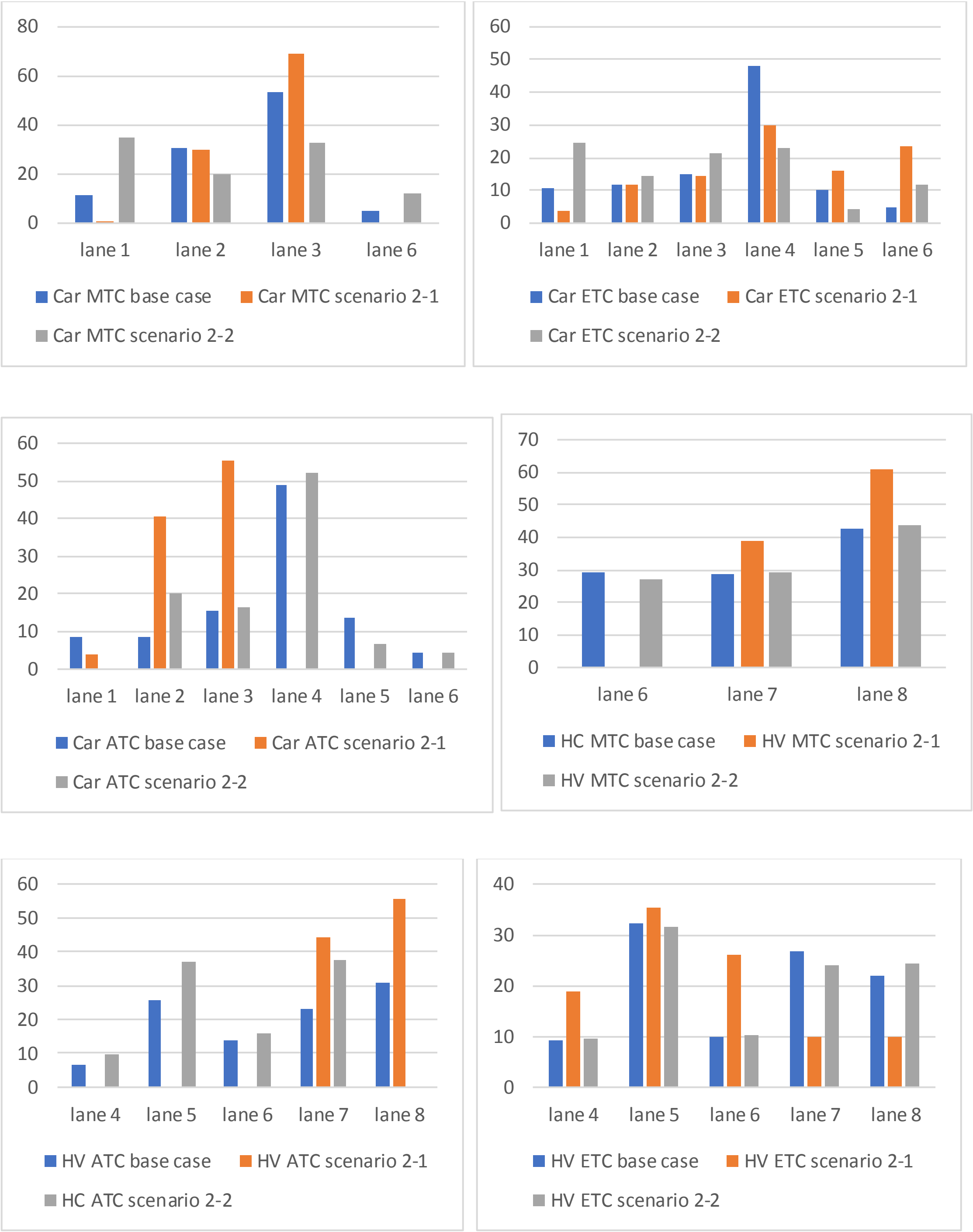


FIGURE 5-2. AVERAGE PERCENTAGE OF EXIT VEHICLES BY VEHICLE TYPE, TOLL PAYMENT METHOD AND TOLL BOOTH IN EXPERIMENT 2

Delay and queue length

Average delay for the entire road network was compared among the three scenarios as shown in Table 5-15. Table 5-15 shows that the average delay for all vehicles was lower for Scenarios 2-1 and 2-2 than the Base case. Although the two proposed toll configurations did not significantly affect the overall delay, converting Lanes 4 to 6 to ETC-only lanes (Scenario 2-1) was relatively more effective in reducing the delay than converting Lanes 1 and 8 to MTC/ETC-only lanes (Scenario 2-2).

However, the average delay for each vehicle type was almost similar in the three scenarios. Thus, unlike prior expectation, opening ETC-only lanes did not significantly reduce the delay for the vehicles with ETC. This is potentially because by opening Lanes 4 to 6 to only ETC vehicles, more MTC and ATC vehicles had to use Lanes 1 to 3 and 7 and 8 compared to Base case as shown in Figure 5-2. Consequently, the ETC vehicles which used these lanes had to stop behind higher number of MTC and ATC vehicles and waited longer in a queue. Although the delay for ETC vehicles decreased in Lanes 4 to 6 due to non-stop toll payment, the total delay for ETC vehicles did not decrease significantly due to the increased delay in Lanes 1 to 3 and 7 and 8. However, the total delay was lowest for Scenario 2-1 among the three scenarios.

Table 5-15. Comparison of average delay per vehicle (seconds) in Experiment 2

Scenarios	All	Car MTC	Car ATC	Car ETC	HV MTC	HV ATC	HV ETC
Base	23.6	33.4	14.9	10.4	45.4	18.2	17
2-1	22.8	31.8	14.5	10.35	44	18.2	16.7
2-2	23	32.2	14.5	10.3	44.3	18.1	16.8

Average queue length and maximum queue length for the entire road network were also compared among the three scenarios as shown in Table 5-16. Table 5-16 shows that Lanes 1 to 3 and Lane 6 had higher queue length in Scenarios 2-1 and 2-2 than Base case. On the other hand, Lanes 4, 5, 7, and 8 had shorter queue length in Scenarios 2-1 and 2-2 than Base case. Overall, the proposed two toll lane configurations resulted in more even distribution of queue length across different lanes than Base case. Similar queue length in different toll lanes is more likely to reduce the number of lane changes. For this reason, the delay was relatively lower for Scenarios 2-1 and 2-2 than Base case as shown in Table 5-15. This result suggests that the current toll lane configuration needs to be changed to reduce the delay for the current traffic demand.

Table 5-16. Comparison of queue length in Experiment 2

	Base case		Scenario 2-1		Scenario 2-2	
Toll lanes	Average queue length	Maximum queue length	Average queue length	Maximum queue length	Average queue length	Maximum queue length
Lanes 1,2,3	12.9	81.7	16.3	76	13.1	68.8
Lanes 4,5	31.9	100.7	24	92.7	24.6	90.7
Lane 6	6.2	71.8	10.4	81.8	7.5	67.5
Lanes 7,8	24.1	101.4	15	87.4	20.1	83.6

Rear-end collision risk

Average time-to-collision (TTC) for all vehicle types before the entry gate was also compared among the three scenarios. It was found that the average TTC for all lanes in Scenario 2-1 (21.3 s) was significantly longer than Base case (14.6 s) and Scenario 2-2 (14.9 s) as shown in Table 5-17. This shows that the new proposed configuration in Scenario 2-1 can more effectively reduce rear-end collision risk upstream of the toll booth than the other configurations.

Table 5-17 also shows that the two proposed configurations can more effectively reduce rear-end collision risk in different lanes. The new proposed configuration in Scenario 2-2 can reduce rear-end collision risk in Lane 3 and the proposed configuration in Scenario 2-1 can reduced rear-end collision risk in Lanes 4 to 6 (ETC-only lanes).

Table 5-17. Comparison of average TTC (seconds) by toll booth before the entry gate in Experiment 2

Toll booth	Base case	Scenario 2-1	Scenario 2-2
Lane 1	7.9	25.9	15.7
Lane 2	9.4	28.2	27.3
Lane 3	13.9	11.3	**21**
Lane 4	13.7	**20.2**	11.1
Lane 5	14.8	**22**	12
Lane 6	23.6	**33.8**	20.5
Lane 7	20.9	21.9	24.9
Lane 8	10.7	13.7	11.4
Average	**14.6**	**21.3**	**14.9**

The duration of time when TTC was less than the threshold of TTC (Time Exposed Time to collision (TET)) (= 1.5 s) upstream of the toll booth was also compared among the three scenarios. It was found that TET was lower for Scenario 2-1 (11236) and Scenario 2-2 (11581) than Base case (11458). This indicates that both toll lane configurations decreased the frequency of safety critical events.

Lane-change collision risk

The Required Braking Rates (RBR) for sideswipe collision risk and rear-end collision risk during lane changes were also estimated using the ACPM method. Table 5-18 shows that average values of RBR for sideswipe conflicts during lane changes were lower for Scenarios 2-1 and 2-2 than Base case. Thus, two proposed configurations did not only reduce rear-end collision risk, but also sideswipe collision risk during lane changes. In contrary, average values of RBR for rear-end conflicts during lane changes were higher for Scenarios 2-1 and 2-2 than Base case.

Besides RBR, the average number of conflicts in each scenario was also measured as shown in Table 5-18. As described in Chapter 5.2.5, the conflict was defined as the event when RBR for each lane change is greater than maximum available braking rate (MABR) of 2.4 m/s^2 (= 8 ft/s^2) (CDM Smith, 2014). The average number of conflicts in all the three scenarios was very low (less than one).

Table 5-18. Average required braking rates (RBR) (m/s^2) and number of conflicts during lane changes in Experiment 2

	Base case	Scenario 2-1	Scenario 2-2
Average RBR (sideswipe)	0.34	0.24	0.3
No. of sideswipe conflicts	0.6	0.6	1
Average RBR (rear-end)	0.19	0.21	0.31
No. of rear-end conflicts	0.6	0.4	0.4

The numbers of sideswipe and rear-end conflicts during lane changes were also separately compared for the 4 types of lane-changing vehicle and training vehicle in the target lane as shown in Tables 5-19 and 5-20. It was found that both new lane configurations reduced the required braking rates during lane changes for all vehicle types except HV-HV for rear-end conflicts. This implies that converting Lanes 4 to 6 to ETC-only lanes and converting Lanes 1 and 8 to MTC/ETC-only lanes can reduce lane-change collision risk. In particular, ETC-only lanes can more effectively reduce the number of severe conflicts (i.e., Car-HV and HV-Car) than converting Lanes 1 and 8 to MTC/ETC-only lanes.

Table 5-19. Average required braking rates (m/s^2) for sideswipe conflicts during lane changes in Experiment 2

$RBR_{LC\text{-}SS}$	Base case	Scenario 2-1	Scenario 2-2
Car-Car	0.26	0.16	0.13
Car-HV	**0.56**	**0.17**	**0.32**
HV-HV	0.40	0.41	0.32
HV-Car	**0.48**	**0.24**	**0.38**

Table 5-20. Average required braking rates (m/s^2) for rear-end conflicts during lane changes in Experiment 2

$RBR_{LC\text{-}RE}$	Base case	Scenario 2-1	Scenario 2-2
Car-Car	0.27	0.14	0.12
Car-HV	**0.21**	**0.11**	**0.22**
HV-HV	0.24	0.49	0.48
HV-Car	**0.34**	**0.16**	**0.22**

In summary, since Scenario 2-1 showed lower delay and rear-end/lane-change collision risk than Base case and Scenario 2-3, converting Lanes 4-6 to ETC-only lanes is recommended when the toll information is displayed via VMS before the merge area.

5.3 Experiment 3 – Impacts of current and new toll lane configuration for different percentages of HV

5.3.1. Description of scenarios

This scenario assessed the impacts of the current and new toll lane configuration with the toll information system (VMS before the merge area) on performance and safety for different percentages of HV which are higher than the current percentage (50%). The following two scenarios of different percentages of HV in the same total traffic demand (i.e., 600 vehicles per hour) were tested: 1) 60% (240 cars and 360 HVs) and 2) 70% (180 cars and 420 HVs). Also, the scenario also assessed the impact of different toll lane configuration for these different percentages of HV. To accommodate higher traffic demand of HV, Lane 6 was only open to HVs with all toll payment methods in a new toll lane configuration. The following four scenarios were tested:

1. Scenario 3-1: Current toll lane configuration in 60% HVs and 40% cars
2. Scenario 3-2: Convert Lane 6 to a HV-only lane in 60% HVs and 40% cars
3. Scenario 3-3: Current toll lane configuration in 70% HVs and 30% cars
4. Scenario 3-4: Convert Lane 6 to a HV-only lane in 70% HVs and 30% cars

Proportions of toll lane use for different toll payment methods in Scenarios 3-2 and 3-4 were assumed for cars and HVs separately as shown in Table 5-21.

Table 5-21. Proportions of toll lane use by vehicle type and toll payment method for converting Lane 6 to HV-only lane

	Toll Lane							
	Car MTC/ETC/ATC			All ETC/ATC		HV MTC/ETC/ATC		
Vehicle Type	1	2	3	4	5	6	7	8
MTC Car	100%			N/A		N/A	N/A	
ETC/ATC Car	35%			65%		N/A	N/A	
MTC HV	N/A			N/A		100%		
ETC/ATC HV	N/A			30%		70%		

Scenario 3-1 was compared with Scenario 3-2 and Scenario 3-3 was compared with Scenario 3-4. Scenarios 3-1 and 3-3 were also compared with Base case (Scenario 1-3) to assess the impacts of different percentages of HV (50%, 60% an 70%) on performance and safety for the current toll lane configuration. The results were provided in the next sections.

5.3.2 Comparison of current and new toll lane configurations for 60% HVs and 40% cars

Table 5-22 shows that converting Lane 6 to a HV-only lane resulted in more even distribution of vehicles across Lanes 6 to 8 than the current configuration. This is because HVs with ETC and ATC used Lane 6 more but used Lanes 4 and 5 less when Lane 6 was only open to HVs compared to the current configuration.

Table 5-22. Average number and percentage of exit vehicles by toll booth in 60% HVs and 40% cars

Toll booth	Scenario 3-1 (Current configuration)		Scenario 3-2 (Convert Lane 6 to a HV-only lane)	
Lane 1	22	3.6%	21.6	3.6%
Lane 2	41.4	6.9%	41	6.8%
Lane 3	73	12.1%	78.4	13%
Lane 4	114.8	19%	105.8	17.5%
Lane 5	111.4	18.5%	96	16%
Lane 6	56	9.3%	75.8	12.5%
Lane 7	93.4	15.5%	94.2	15.6%
Lane 8	89.6	14.9%	90.2	15%

Delay and queue length

Table 5-23 shows that the average delay for all vehicles in the entire road network was slightly lower for Scenario 3-2 than Scenario 3-1. Moreover, the average delay for each vehicle type was almost similar in two scenarios. So, converting Lane 6 to a HV-only lane for 60% HV did not significantly reduce the average delay for all vehicles.

Table 5-23. Comparison of average delay per vehicle (seconds) in 60% HVs and 40% cars

Scenarios	All	Car MTC	Car ATC	Car ETC	HV MTC	HV ATC	HV ETC
3-1	23	31.9	14.5	10.4	44	18.1	17
3-2	22.7	30.8	14.2	10.3	43.2	18.1	17

Table 5-24 shows that Lane 6 had higher average queue length in Scenario 3-2 than Scenario 3-1. This is due to higher HV demand for Lane 6 in Scenario 3-2 as shown in Table 5-22 as this lane was open to only one type of vehicle. The average queue length in other lanes were almost similar in the two scenarios.

Table 5-24. Comparison of queue length in 60% HVs and 40% cars

	Scenario 3-1		Scenario 3-2	
Toll lanes	Average queue length	Maximum queue length	Average queue length	Maximum queue length
Lanes 1,2,3	10.7	81	10.6	81.2
Lanes 4,5	32.7	103.2	31.2	107.6
Lane 6	7	75.7	10	86
Lanes 7,8	29.1	105.7	30.5	114.6

Rear-end collision risk

Average time-to-collision (TTC) for all vehicle types before the entry gate was also compared between the two scenarios. It was found that the average TTC for all lanes in Scenario 3-2 (16.4 s) was slightly longer than Scenario 3-1 (16 s) as shown in Table 5-25. This shows that converting Lane 6 to a HV-only lane for 60% HV did not significantly reduce rear-end collision risk upstream of the toll booth.

The Table 5-25 also shows that the average values of TTC for different lanes were almost similar in the two scenarios except Lanes 5 and 7. The new proposed configuration reduced rear-end collision risk in Lane 7.

Table 5-25. Comparison of average TTC (seconds) by toll booth before the entry gate in Experiment 3

Toll booth	Scenario 3-1	Scenario 3-2
Lane 1	8	8
Lane 2	10.1	10.6
Lane 3	10.2	12
Lane 4	12	12
Lane 5	15.6	11.6
Lane 6	20.6	19.2
Lane 7	26.2	30
Lane 8	14.6	14.7
Average	**16.0**	**16.4**

It was also found that TET for Scenario 3-2 (11110) was higher than Scenario 3-1 (10967). This indicates that converting Lane 6 to a HV-only lane for 60% HV rather increased the frequency of safety critical events.

Lane-change collision risk

Table 5-26 shows that average values of RBR for sideswipe conflicts during lane changes was lower for Scenario 3-2 than Scenario 3-1. Thus, converting Lane 6 to a HV-only lane reduced sideswipe collision risk during lane changes. However, average values of RBR for rear-end conflicts during lane changes in Scenarios 3-2 and 3-1 were the same. Thus, the proposed configuration did not rear-end collision risk during lane changes. Besides RBR, the average number of conflicts in each scenario was also measured as shown in Table 5-26. The average number of conflicts in two scenarios was very low (equal or less than one).

Table 5-26. Average required braking rates (RBR) (m/s^2) and number of conflicts during lane changes in 60% HVs and 40% cars

	Scenario 3-1	Scenario 3-2
Average RBR (sideswipe)	0.42	0.37
No. of sideswipe conflicts	0.2	0.4
Average RBR (rear-end)	0.3	0.3
No. of rear-end conflicts	0.6	1

The numbers of sideswipe and rear-end conflicts during lane changes were also separately compared for the 4 types of lane-changing vehicle and trailing vehicle in the target lane as shown in Tables 5-27 and 5-28. It was found that Scenarios 3-2 generally shows higher RBR for both sideswipe and rear-end conflict during lane changes than Scenario 3-1 for all vehicle types except HV-HV. In particular, Scenario 3-2 showed higher RBRs for Car-HV and HV-Car. Thus, converting Lane 6 to a HV-only lane for 60% HV is not effective in reducing the number of severe conflicts.

Table 5-27. Average required braking rates (m/s^2) by type of lane-changing and trailing vehicles for sideswipe conflicts during lane changes in 60% HVs and 40% cars

$RBR_{LC\text{-}SS}$	Scenario 3-1	Scenario 3-2
Car-Car	0.12	0.13
Car-HV	**0.62**	**0.89**
HV-HV	0.48	0.37
HV-Car	**0.4**	**0.41**

Table 5-28. Average required braking rates (m/s^2) by type of lane-changing and trailing vehicles for rear-end conflicts during lane changes in 60% HVs and 40% cars

$RBR_{LC\text{-}RE}$	Scenario 3-1	Scenario 3-2
Car-Car	0.07	0.09
Car-HV	**0.24**	**0.83**
HV-HV	0.45	0.26
HV-Car	**0.32**	**0.42**

Although converting Lane 6 to a HV-only lane slightly reduced the average delay, it increased rear-end/lane-change collision risk compared to the current toll lane configuration. Thus, the proposed new lane configuration for 60% HV is not recommended from a safety perspective.

5.3.3 Comparison between current and new toll lane configurations for 70% HVs and 30% cars

The impact of converting Lane 6 to a HV-only lane on performance and safety was also assessed for 70% HV. Table 5-29 shows that the new toll lane configuration resulted in more even distribution of vehicles across Lanes 6 to 8 than the current configuration similar to 60% HV.

Table 5-29. Average number and percentage of exit vehicles by toll booth in 70% HVs and 30% Cars

Toll booth	Scenario 3-3 (Current configuration)		Scenario 3-4 (Convert Lane 6 to a HV-only lane)	
Lane 1	12.2	2%	10.8	1.8%
Lane 2	29.2	4.8%	27.2	4.5%
Lane 3	59.4	9%	66.8	11.1%
Lane 4	108.2	18%	93.2	15.5%
Lane 5	116.2	19.3%	99.2	16.5%
Lane 6	63	10.5%	88.8	14.7%
Lane 7	108.4	18%	110.8	18.4%
Lane 8	104.4	17.3%	105	17.4%

Delay and queue length

Table 5-30 shows that the average delay for all vehicles was lower for Scenario 3-4 than Scenario 3-3. Moreover, the average delay for each vehicle type was almost similar in two scenarios. Similar to 60% HV, converting Lane 6 to a HV-only lane for 70% HV did not significantly reduce the average delay for all vehicles.

Table 5-30. Comparison of average delay per vehicle (seconds) in 70% HVs and 30% Cars

Scenarios	All	Car MTC	Car ATC	Car ETC	HV MTC	HV ATC	HV ETC
3-3	23	31.3	14.3	10.4	43.6	18.2	17.1
3-4	22.6	30.3	14	10.3	42.8	18.2	17.1

Table 5-31 shows that Lane 6 had higher average queue length in Scenario 3-4 than Scenario 3-3 for 70% HV similar to 60% HV. However, the average queue length increased in HV-only lanes (Lanes 6 to 8) due to higher number of HVs compared to 60% HV.

Table 5-31. Comparison of queue length in 70% HVs and 30% Cars

	Scenario 3-3		Scenario 3-4	
Toll lanes	Average queue length	Maximum queue length	Average queue length	Maximum queue length
Lanes 1,2,3	10	83.1	10.2	83
Lanes 4,5	34.6	108.4	31.4	109.8
Lane 6	8	81.4	12.4	93.2
Lanes 7,8	32.7	111.3	33.2	118

Rear-end collision risk

Average time-to-collision (TTC) for all vehicle types upstream of the toll booth was longer for Scenario 3-4 (20.8 s) than Scenario 3.3 (19.1 s) as shown in Table 5-32. This percentage increase in TTC for 70% HV (14%) was much higher than the percentage increase for 60% HV (2.5%). This shows that converting Lane 6 to a HV-only lane can more effectively reduce rear-end collision risk for higher percentage of HV. Table 5-32 also shows that the average values of TTC for different lanes were relatively similar between two scenarios except Lane 7.

Table 5-32. Comparison of average TTC (seconds) by toll booth before the entry gate in Experiment 3

Toll booth	Scenario 3-3	Scenario 3-4
Lane 1	7.8	7.7
Lane 2	11.1	11
Lane 3	8.6	8.5
Lane 4	11.9	12.5
Lane 5	16.8	16.8
Lane 6	25.2	26.3
Lane 7	29.4	32.5
Lane 8	19.5	20.3
Average	**19.1**	**20.8**

It was also found that TET for Scenario 3-4 (10248) was lower than Scenario 3-3 (10331). Thus, the proposed lane configuration can reduce rear-end collision risk and frequency of safety critical events for 70% HV.

Lane-change collision risk

Table 5-33 shows that average values of RBR for sideswipe and rear-end conflicts during lane changes was higher for Scenario 3-4 than Scenario 3-3 unlike 60% HV. Thus, the proposed configuration rather increased lane-change collision risk for 70% HV than 60% HV. This indicates that higher number of HV resulted in more frequent lane changes of HV when higher number of HV-only lanes was open. However, the average number of conflicts in each scenario was very low similar to 60% HV.

Table 5-33. Average required braking rates (RBR) (m/s^2) and number of conflicts during lane changes in 70% HVs and 30% Cars

	Scenario 3-3	Scenario 3-4
Average RBR (sideswipe)	0.42	0.44
No. of sideswipe conflicts	1.2	0.8
Average RBR (rear-end)	0.56	0.6
No. of rear-end conflicts	0.6	1.4

Tables 5-34 and 5-35 show that the RBRs for both sideswipe and rear-end conflicts during lane changes were lower for Scenario 3-4 than Scenario 3-3 for Car-Car (car changing lane in front of trailing car in the target lane) and Car-HV (car changing lane in front of trailing HV in the target lane). In contrary, RBRs were higher for Scenario 3-4 than Scenario 3-3 for HV-Car and HV-HV. This result of 70% HV was different from the result for 60% HV. This indicates that as the number of HV increases, the number of lane-changing HV and the risk of lane-change collision with the trailing car or HV in the target lane also increase. Thus, converting Lane 6 to a HV-only lane has mixed effects on severe lane-change conflicts – it reduced the collision risk for Car-HV but increased the collision risk for HV-Car.

Table 5-34. Average required braking rates (m/s^2) by type of lane-changing and trailing vehicles for sideswipe conflicts during lane changes in 70% HVs and 30% Cars

$RBR_{LC\text{-}SS}$	Scenario 3-3	Scenario 3-4
Car-Car	0.12	0.07
Car-HV	**0.83**	**0.45**
HV-HV	0.54	0.56
HV-Car	**0.29**	**0.34**

Table 5-35. Average required braking rates (m/s^2) by type of lane-changing and trailing vehicles for rear-end conflicts during lane changes in 70% HVs and 30% Cars

$RBR_{LC\text{-}RE}$	Scenario 3-3	Scenario 3-4
Car-Car	0.12	0.07
Car-HV	**0.72**	**0.3**
HV-HV	0.87	1.12
HV-Car	**0.22**	**0.77**

In summary, converting Lane 6 to a HV-only lane showed marginal benefit of reducing the delay for higher percentages of HV than the current percentage (50%). This new toll lane configuration also reduced rear-end collision risk, particularly higher reduction for higher percentage of HV. However, the new configuration rather increased lane-change collision risk, particularly higher collision risk of lane-changing HV for higher percentage of HV. Thus, converting Lane 6 to a HV-only lane is recommended to reduce rear-end collision risk but more restriction of lane changes is required to prevent an increase in lane-change collision risk.

5.4 Impacts of different percentages of HV for current toll lane configuration

Based on the results in Chapters 5.1-5.3, the impact of different percentages of HV on performance and safety for the current toll lane configuration was also assessed. Table 5-36 compares average number and percentage of exit vehicles by toll booth among different percentages of HV – 50%, 60% and 70%. It was found that the percentage of exit vehicles continuously increased for Lane 6 (all MTC/ETC/ATC lane) and Lanes 7 and 8 (HV-only lanes) as the percentage of HV increased. This resulted in more even distribution of exit vehicles in Lanes 4 to 8.

Table 5-36. Average number and percentage of exit vehicles by toll booth for different percentages of HV

Toll booth	Base case (50% HV)		Scenario 3-1 (60% HV)		Scenario 3-3 (70% HV)	
Lane 1	30.8	5.1%	22	3.6%	12.2	2%
Lane 2	51.4	8.5%	41.4	6.9%	29.2	4.8%
Lane 3	84.6	14.1%	73	12.1%	59.4	9%
Lane 4	123.8	20.6%	114.8	19%	108.2	18%
Lane 5	107.8	17.9%	111.4	18.5%	116.2	19.3%
Lane 6	51.2	8.5%	56	9.3%	63	10.5%
Lane 7	78.4	13.0%	93.4	15.5%	108.4	18%
Lane 8	74.2	12.3%	89.6	14.9%	104.4	17.3%

Table 5-37 shows that the average delay for all vehicles was slightly higher for 50% HVs than 60% and 70% HV. Moreover, the average delay for each vehicle type was almost similar for the three percentages of HV.

Table 5-37. Comparison of average delay per vehicle (seconds) among different percentages of HV

Scenario	All	Car MTC	Car ATC	Car ETC	HV MTC	HV ATC	HV ETC
50% HV	23.6	33.4	14.9	10.4	45.4	18.2	17
60% HV	23	31.9	14.5	10.4	44	18.1	17
70% HV	23	31.3	14.3	10.4	43.6	18.2	17.1

Table 5-38 shows that 70% HVs traffic demand had highest average queue length in Lanes 4 to 8 and lowest average queue length in Lanes 1 to 3. This is due to higher number of HVs and lower number of cars since Lanes 4 to 8 were used by HVs and Lanes 1-3 were used by only Cars.

Table 5-38. Comparison of queue length among different percentages of HV

	50% HV		60% HV		70% HV	
Toll lanes	Average queue length	Maximum queue length	Average queue length	Maximum queue length	Average queue length	Maximum queue length
Lanes 1,2,3	12.9	81.7	10.7	81.0	10.0	83.1
Lanes 4,5	31.9	100.7	32.7	103.2	34.6	108.4
Lane 6	6.2	71.8	7.0	75.7	8.0	81.4
Lanes 7,8	24.1	101.4	29.1	105.7	32.7	111.3

Rear-end collision risk

Table 5-39 shows that the average TTC for all lanes increased as the percentage of HV increased as shown in Table 5-39. So, higher percentage of HV decreases rear-end collision risk upstream of the toll booth. In particular, higher percentage of HV decreased rear-end collision in Lanes 2, 5, 7 and 8 and increased rear-end collision in Lanes 3 and 4.

Table 5-39. Comparison of average TTC (seconds) among different percentages of HV

Toll booth	50% HV	60% HV	70% HV
Lane 1	7.9	8	7.8
Lane 2	9.4	10.1	11.1
Lane 3	13.9	10.2	8.6
Lane 4	13.7	12	11.9
Lane 5	14.8	15.6	16.8
Lane 6	23.6	20.6	25.2
Lane 7	20.9	26.2	29.4
Lane 8	10.7	14.6	19.5
Average	**14.6**	**16**	**19.1**

As it was mentioned before, TET was 11458 for 50% HV, and 10967 for 60% HV and 10331 for 70% HV. So, the frequency of safety critical events decreased as the percentage of HV increased.

Lane-change collision risk

Table 5-40 shows that average values of RBR for sideswipe and rear-end conflicts during lane changes were lower for 50% HV than 60% and 70% HV. Thus, lower percentage of HV decreased sideswipe and rear-end collision risk during lane changes.

Table 5-40. Average required braking rates (RBR) (m/s^2) and number of conflicts during lane changes for different percentages of HV

	50% HV	60% HV	70% HV
Average RBR (sideswipe)	0.34	0.42	0.42
No. of sideswipe conflicts	0.6	0.2	1.2
Average RBR (rear-end)	0.19	0.3	0.56
No. of rear-end conflicts	0.6	0.6	0.6

The numbers of sideswipe and rear-end conflicts during lane changes were also separately compared for the 4 types of lane-changing vehicle and trailing vehicle in the target lane as shown in Tables 5-41 and 5-42. It was found that higher percentage of HV shows higher RBR for both sideswipe and rear-end conflicts during lane changes for cars as the lane changing vehicles and HVs as the trailing vehicles. In contrast, it was found that higher percentage of HV shows lower RBR for both sideswipe and rear-end conflict during lane changes for HVs as the lane changing vehicles and Cars as the trailing vehicles. Thus, higher percentage of HVs can have differential effects on the lane-change collision risk for different types of lane-changing and trailing vehicles.

Table 5-41. Average required braking rates (m/s^2) for sideswipe conflicts during lane changes for different percentages of HV

$RBR_{LC\text{-}SS}$	50% HV	60% HV	70% HV
Car-Car	0.26	0.12	0.12
Car-HV	**0.56**	**0.62**	**0.83**
HV-HV	0.40	0.48	0.54
HV-Car	**0.48**	**0.4**	**0.29**

Table 5-42. Average required braking rates (m/s^2) for rear-end conflicts during lane changes for different percentages of HV

$RBR_{LC\text{-}RE}$	50% HV	60% HV	70% HV
Car-Car	0.27	0.07	0.12
Car-HV	**0.21**	**0.24**	**0.72**
HV-HV	0.24	0.45	0.87
HV-Car	**0.34**	**0.32**	**0.22**

In summary, for the current toll lane configuration, higher percentage of HV increased the exit volume of toll lanes for HVs and decreased the exit volume of toll lanes for cars. This resulted in slight reduction in delay. However, higher percentage of HV increased lane-change collision risk although it reduced rear-end collision risk. Thus, the current toll lane configuration needs to be adjusted to ensure safe lane changes when the percentage of HV increases.

6. CONCLUSIONS AND RECOMMENDATIONS

This study investigated the impacts of the toll information system on the traffic performance and the collision risk at a toll plaza. This study also investigated the impacts of different toll lane configuration with the toll information system for current traffic demand and different percentages of heavy vehicles (HV) on the delay and the collision risk. The proposed toll information system displays real-time status of toll lane configuration with different toll payment methods and vehicle types (cars and HVs) via variable message signs (VMS) upstream of toll booth. There are 3 toll payment methods - manual toll collection (MTC), automatic toll collection (ATC) and electronic toll collection (ETC).

To evaluate the impacts, the traffic flow at the toll plaza on the Gordie Howe International Bridge – a new bridge under construction at the Windsor-Detroit international border crossing - was simulated using the VISSIM microscopic traffic simulation. The current toll lane configuration was assumed to be 8 toll lanes - 3 car-only lanes, 3 car-HV shared lanes and 2 truck-only lanes.

Three experiments were performed in this study. In Experiment 1, the impacts of presence and location of VMS were assessed for the current peak-hour traffic demand and toll lane configuration. Three scenarios (no VMS, VMS 140 m from the entry gate, and separate VMS for cars and HVs 75 m before the merge point) were tested and compared. In Experiment 2, the impacts of different toll lane configurations with the best scenario of Experiment 1 were assessed. Two scenarios (converting the toll lanes with multiple toll payment methods to ETC-only lanes and converting two MTC/ATC/ETC lanes to MTC/ETC-only lanes) were tested and compared. In Experiment 3, the impacts of the current and new toll lane configuration with the best scenario of Experiment 1 were assessed for two different percentages of HV (60% and 70% HV). For each percentage of HV, two scenarios (the current toll lane configuration and the increase in the number of HV-only lanes from 3 to 4) were tested and compared. Also, based on the results in these experiments, the impacts of different percentages of HV (50, 60 and 70%) were compared for the current toll lane configuration. Main findings are summarized as follows:

First, the toll information system helps reduce the delay and rear-end/lane-change collision risk. In particular, two separate VMS for cars and HVs before the merge point showed the better result than the VMS after the merge point and closer to the toll booth. This is because the VMS helped drivers make earlier decision to choose the toll booth with specific toll payment methods.

Second, the effectiveness of toll information system in reducing the delay and collision risk can be further enhanced by implementing different toll lane configuration. In particular, installation of ETC-only lanes significantly reduced rear-end and lane-change collision risk compared to the current toll lane configuration. This is because ETC vehicles are not required to stop at the toll booth to pay the toll unlike MTC and ATC vehicles.

Third, the effectiveness of toll information system in reducing the delay and collision risk can vary as the percentage of HV increases. With the toll information system, increasing the number of HV-only lanes to accommodate the increased HV traffic demand rather increased lane-change collision risk compared to the current configuration. Also, lane-change collision risk increased as the percentage of HV increased for the current configuration. This is because more HVs changed lanes to use the designated toll lane with shorter queue length when the number of HVs was higher.

In conclusion, the toll information system can potentially provide benefits of lower delay and lower collision risk at the toll plaza by helping drivers make earlier route decision to choose the toll lane. Also, the toll information system with variable toll lane configuration which accommodates different traffic demand can increase the effectiveness of the system in improving traffic performance and safety.

However, there are some limitations in this study so future studies are recommended as follows. First, only a limited number of scenarios were tested in this study. Thus, it is recommended to assess more scenarios (different traffic demand for cars and HVs, different toll lane configurations) to observe the general pattern of impacts of traffic demand and toll lanes on traffic performance and safety.

Second, surrogate safety measures used for assessment of lane-change collision risk in this study have some limitations such as not considering the trailing vehicles that have lower speed than the lane-changing vehicles. Thus, it is also recommended to develop a new surrogate safety measure that can better capture lane-change collision risk for various situations of lane changes.

Lastly, since the Gordie Howe International Bridge was under construction, real-world driver behaviour at the toll plaza could not be observed and the simulation results could not be validated in this study.

In future studies, it is recommended to collect real-world driver behavior data from actual toll plaza and use the validated simulation model to evaluate the impacts of the toll information system. It is also recommended to analyze the effect of driver experience on toll lane selection. Since the drivers who regularly or frequently cross the bridge (e.g., commuters) will have better knowledge of the toll lane configuration from their experience, their behaviors are likely to be different from the other drivers.

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