Using ITS to improve the capacity of freeway merging sections by transferring freight vehicles

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1. Introduction

Freight transport by road is growing fast all around the world. Road freight dominates with 80 percent of the market for distances of less than 100 kilometres. For instance, about 1553 million tonnes of freight are transported around Australia by road each year and truck traffic is forecast to double over the next 20 years [1]. Freeways comprise about 5 to 10 percent of the road network, nevertheless they carry around 30 to 40 percent of all vehicle traffic. More than 40 percent of freeway traffic congestion occurs at freeway bottlenecks due to their limited physical capacity while traffic incidents count for only 25 percent of freeways congestion [2]. Freeway merging sections form bottlenecks when they are under heavy demand with a high proportion of heavy commercial vehicles [3]. Despite this, there has been no fundamental research to identify the effects of heavy commercial vehicles on the capacity and overall performance of congested freeway merging sections. The continued efficient movement of freight is a major concern since it can be linked to overall economic efficiency, employment and the affordability of consumer products. It is vital to examine how future main roads will handle the increasing number of heavy commercial vehicles.

The acceleration and merging process from an entrance ramp onto the freeway lanes constitutes an important aspect of freeway traffic operations and ramp junction geometric design. Competing traffic demands for space influence this process regarding both the ramp freeway junction and the upstream freeway lanes. A driver approaching from a ramp must make a series of decisions and carry out control tasks, all affected by the driver’s capability to process the roadway and traffic information and interpret it into speed and position control responses. This complex driving situation involves both internal factors: driver attitude and vehicle characteristics, and external factors: freeway speed, lane changing maneuvers, relative positions of merging vehicles, and proximity of the merging vehicle to the merge end. These tasks are even more challenging for heavy commercial vehicles due to their large size and confined operational characteristics compared to passenger cars. Ramp vehicles acceleration-deceleration characteristics are also essential components in microscopic simulation modeling for simulating the merging freeway entrance ramp.

The freeway ramp merging process has been studied since the 1940s [4,5,6,7,8]. Research on driver behavior during on-ramp merging process and the effect of ramp geometric design and traffic characteristics has primarily focused on free flow conditions and specifically in relation to passenger cars [9,10,11,12,13,14]. The operational performance of trucks under free flow conditions has received extensive attention [15,16,17]. There is also much research conducted to examine the relationship of ramp sections design and truck accident rates [18,19,20]. Traffic conditions in which the demand exceeds the capacity might induce special driver behavior. However, due to the lack of sufficient data in congested traffic situation, the effects of traffic and geometric characteristics on the merging capacity and merging traffic behavior and characteristics are largely unknown. In order to investigate these problems, a three year extensive study was undertaken to focus on the merging process under congested freeway traffic conditions. For this purpose, extensive data obtained from observation, survey and detector data in Tokyo and the necessary data such as spacing and relative speeds of merging vehicles are extracted. The collected field data, such as freeway and ramp vehicle speeds, acceleration-deceleration rates, and merging positions were used to identify and quantify key variables for use in the freeway merging model. The field data were applied to the established driver behavior concepts in order to examine the proposed methodologies for freeway merging behavior. Based on this behavioral model, the Freeway Merging Capacity Simulation Program (FMCSP) was developed to simulate the actual traffic conditions. This model evaluates the capacity of a merging section for a given geometric. Moreover, the extensive collected detector data were used to measure the effect of heavy commercial vehicles percentage on the capacity of merging sections.

2. Evaluation of the Heavy Commercial Vehicles Impacts on the Traffic Behavior and Characteristics of Merging Sections

2.1 Data

In order to study the effect of heavy vehicles on the traffic characteristics and behavior of merging section under congested conditions, date are collected. The data collected in this study is based on the Hamazaki-bashi and Ichinohashi merging points in Tokyo. Macroscopic data collected by mainly detectors. Detectors collected speed, occupancy, flow rate, and type of vehicles in one-minute interval at two merging sections for a period of three years [21].

From the detector data, the period is selected which is fully congested;" i.e., queues reside on both freeway and merge approaches and there is no exogenous flow restriction from downstream. For the microscopic data collection traffic streams were recorded using several video cameras mounted on the top of the buildings in the vicinity of the merging sections and a total of 16 hours of recording was collected. The tapes were first reviewed and a number of merging maneuvers were identified and then each maneuver was analyzed in microscopic detail. The position and speed of each vehicle involved in the merging maneuver were identified at 0.15 seconds interval using frame by frame image processing technique. Through this microscopic analysis, time-series data of vehicle position, velocities, and accelerations were stored for about 200 merging maneuvers (159 cars and 41 heavy commercial vehicles). From the trajectory data, front/rear spacing, relative speeds, accelerations of merging and adjacent vehicles were analyzed. These variables must be closely related to each other, that is, merging vehicles would not consider only spacing or relative speeds but also the interrelationship among these variables, when they perform merging maneuver.

2.2 Methodologies for Modeling Ramp Driver Acceleration-Deceleration Behavior

Freeway merge maneuvers are complex procedures involving various steps, for example a lane change, continuous acceleration, deceleration, and finally merging into a gap. The process of acceleration and merging from an entrance ramp into the freeway lanes constitutes an important consideration for freeway traffic operations and the design of ramp junctions. The acceleration-deceleration characteristics of ramp vehicles in the acceleration lane are essential components of all microscopic simulation models designed to simulate merging from a freeway entrance ramp. The primary objective of this part of the study was to analytically investigate the merging behavior of ramp drivers. This investigation, which considered various types of entrance ramp, analyzed driver behavior in terms of the speed of the ramp vehicle relative to its corresponding freeway lead and lag vehicles, and the spacing between the ramp vehicle and the freeway lead and lag vehicles. This investigation was undertaken with a view to developing a methodology that can be used to model ramp driver acceleration-deceleration behavior during freeway merge maneuvers under congested traffic conditions.

The empirical investigation used video and image processing techniques described in preceding section. The resulting traffic data provides fundamental information about the freeway merge behavior of ramp drivers. The merging position of the ramp vehicle was analyzed relative to the freeway lead and lag vehicles. In addition, we examined the relation between merging position and ramp vehicle speed, as well as the effect on merging position of the relative speed and time gap between a ramp vehicle and freeway vehicles at the time of the merging maneuver into the freeway lane. This analysis was performed separately for passenger cars and heavy vehicles. When building our model of the behavior of ramp drivers, existing car-following models are naturally taken into consideration. However, the acceleration-deceleration of ramp vehicles in acceleration lanes is much more complicated than the types of behavior described by conventional car-following models. Essentially, the basis for modeling the acceleration-deceleration behavior of ramp vehicles differs from that of the conventional car-following model. Nevertheless, the fundamental psychophysical concept of the car-following models (*Driver Response(t+T) = Sensitivity factors(t) * Stimulus(t)*, where *t* is the time and *T* is the reaction time) remains appropriate providing the stimuli can be well specified.

Based on comprehensive microscopic analysis [22], three stimuli are considered to affect ramp driver behavior: speed relative to the freeway leader, speed relative to the freeway lag vehicle and the distance from the freeway leader. The equation for the follow-the-leader car-following model is expanded linearly to incorporate the influence of both the freeway lag and lead vehicles. Herman and Rothery [23] proposed a similar concept with regard to a three-car car-following situation. The expression for ramp vehicle acceleration-deceleration behavior of a ramp platoon leader is given in Equation 1.

$$a_R(t+T) = \alpha_0 + \alpha_1 \frac{V_R^m(t+T)}{[X_{Flead}(t) - X_R(t)]^{l_1}} [V_{Flead}(t) - V_R(t)]$$

$$+\alpha_2 \frac{V_R^m(t+T)}{[X_R(t)-X_{Flag}(t)]^{l_2}}[V_R(t)-V_{Flag}(t)]$$
$$+\alpha_3 \frac{1}{[X_{Flead}(t)-X_R(t)]^{l_3}}\{S(t)-f[v(t)]\} \qquad (1)$$

Where:

$a_R(t+T)$: Acceleration rate of the ramp vehicle at time *t*+*T* (m/s^2)
$X_R(t)$: Location of the ramp vehicle at time *t* (m)
$X_{Flead}(t)$: Location of the freeway lead vehicle at time *t* (m)
$X_{Flag}(t)$: Location of the freeway lag vehicle at time *t* (m)
$V_R(t)$: Velocity of the ramp vehicle at time *t* (m/s)
$V_R(t+T)$: Velocity of the ramp vehicle at time *t*+*T* (m/s)
$V_{Flead}(t)$: Velocity of the freeway lead vehicle at time *t* (m/s)
$V_{Flag}(t)$: Velocity of the freeway lag vehicle at time *t* (m/s)
$S(t)=X_{Flead}(t)-X_R(t)$: Spacing between the ramp vehicle and the freeway leader vehicle at time t (m)
$f[v(t)]$: Desired spacing as a function of speed (m)
T : Time lag or driver response time (s)
$\alpha_0,\alpha_1,\alpha_2,\alpha_3,m,l_1,l_2,l_3$ are the parameters to be estimated.

Similar methodology is used to express the acceleration-deceleration behavior of the lag drivers (approaching ramp area from the freeway) and is presented in Sarvi et al. [24]. The second and third terms in Equation 1 represent the conventional model of the reaction of a ramp driver to changes in the speed of the corresponding freeway leader and lag vehicles. The fourth term introduces a spring action related to the spacing between the ramp vehicle and freeway lead vehicle, which causes the follower to accelerate when the spacing is larger than the desired value and decelerate when the spacing is less than the desired value. Data collected at two merging points which incorporated two hundred samples were used to calibrate the hypothesized ramp vehicle acceleration-deceleration models (this analysis is also performed separately for the heavy vehicles).

The results indicated that 90th percentile of ramp drivers respond to stimuli after a time gap of 0.7s. Nonlinear and linear functional forms were used for the calibration of Equation 1 (estimated parameters for the linear model are α_0= -0.134, α_1= 0.73, α_2= -0.51, and for the nonlinear model are α_0= 0.103, α_1=1.84, α_2= -0.5, α_3= 0.134). The correlation coefficients for the two models were R=0.7 for the nonlinear form and R=0.6 for the linear form. In general, the results of the linear and nonlinear response models show acceptable consistency in both sign and magnitude. For example, the best models are found for *T*= 0.7 s and with the inclusion of the freeway leader and lag vehicles. The sign of the corresponding coefficients of the best linear and nonlinear models are all identical. Based on correlation coefficients, the nonlinear models, as expected, perform slightly better than the linear models.

The difference, however, is not great. The small difference between the two models indicates that the optimal linear acceleration-deceleration model is a good approximation that reproduces the interaction between the vehicles reasonably well, in agreement with the findings of Newell [25]. The best fitted nonlinear acceleration-deceleration model of a heavy commercial vehicle is:

$$\begin{aligned} a_R(t+T) &= 0.079 + 1.34\frac{V_R^{0.0002}(t+T)}{[X_{Flead}(t)-X_R(t)]^1}[V_{Flead}(t)-V_R(t)] \\ &\quad - 0.327\frac{V_R^{0.0002}(t+T)}{[X_R(t)-X_{Flag}(t)]^0}[V_R(t)-V_{Flag}(t)] \\ &\quad + 0.112\frac{1}{[X_{Flead}(t)-X_R(t)]^0}\{S(t)-f[v(t)]\} \end{aligned} \tag{2}$$

2.3 General behavior of freeway lag heavy commercial vehicle in the merging area

A freeway lag driver (approaching the ramp area from the freeway nearside lane) in the vicinity of merging area performs different tasks in a timesharing mode particularly in interaction with the ramp vehicle. These behaviors varies across drivers and the outcome of these variations could depict the fundamental aspects of the entrance ramp operations. Following is an overview of the observed phenomena (speed profile) during real merging operations emphasizing the behavior of the freeway lag heavy commercial vehicle.

The primary data of interest is the speed of freeway lag heavy vehicles negotiating the merging section. It provides the speed change profile during the ramp merging maneuver, indicating where and with what magnitude vehicles were accelerating or decelerating in interaction with freeway leader and ramp vehicles. Speed data were calculated by measuring the travel distance between sequential image intervals where a vehicle moves from one image to the next. Figure 1 shows the calculated freeway lag heavy vehicle average speed profile based upon distance from the twenty meters prior to the physical nose. The curve illustrates that on an average sense a freeway lag (truck) driver has a higher speed than ramp driver in the first part of the acceleration lane. This could be interpreted as the result of a competition for the available space between the ramp and the freeway lag vehicles. Then in an average sense either the freeway lag driver decelerates (to accommodate the merging ramp vehicle and avoid collision) or the ramp driver accelerates (to force a merging) on the first step of the freeway ramp merging maneuver. Following this step the truck driver continuously accelerates and follows his leader. For the remaining freeway ramp merging maneuver the freeway leader and ramp vehicles have higher speed than the freeway lag vehicle. In addition, this figure shows a clear speed decline due to the interaction between the ramp vehicle and its freeway lag and leader vehicles during the freeway ramp merging maneuver.

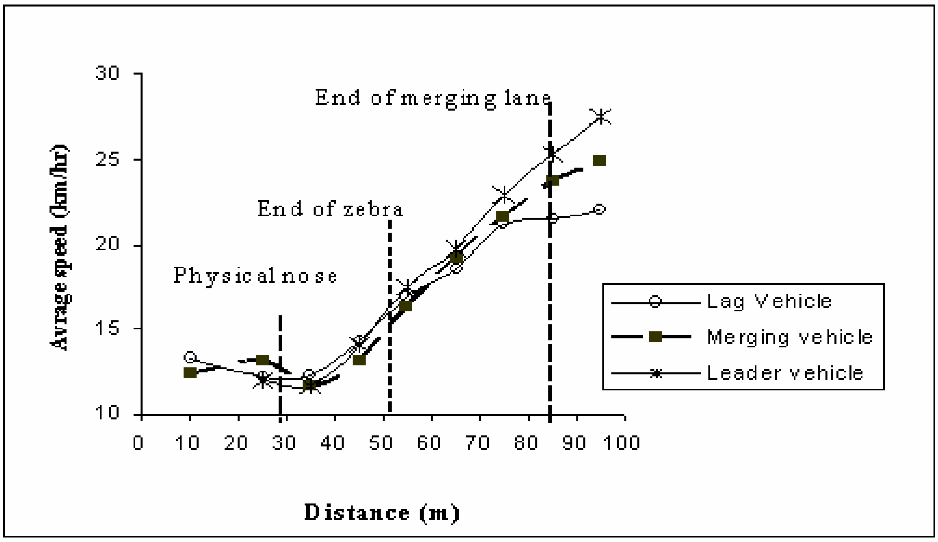

Figure 1. Average freeway lag heavy vehicle and corresponding freeway leader and ramp vehicles speed profile (Ichinohashi merging section).

2.4 FMCSP: A Micro Simulation Model

A periodic sampling method at intervals of 0.05 s is used for this micro-simulation model. The FMCSP simulation includes the merging section and the upstream/downstream sections [26]. These sections are treated as three distinct types, each with its own characteristics .
The FMCSP considers the following: (1) Preliminary segments (ramp and freeway nearside and far-side lanes prior to the merging end): the purpose of these segments is to allow time for the vehicles generated at the upstream ends of the ramp and freeway to form platoons while traveling through the 350 m segment. At the beginning of the freeway segment, vehicles are dynamically generated based on the travel times of vehicles in the freeway nearside and far-side lanes. The merging maneuver makes the travel time of vehicles in the freeway nearside lane greater than that of vehicles in the far-side lane; hence, fewer vehicles are generated in the nearside lane. The shorter travel time of the freeway far-side lane accounts for the tendency of drivers familiar with the merging section to utilize this lane to avoid merging interactions.

The FMCSP also varies vehicle size and acceleration/deceleration performance to simulate vehicles ranging from trucks to light vehicles. Each driver is given a desired speed, which is chosen from a normal distribution at the time the driver's vehicle is generated. (2) Merging segment (ramp and freeway lanes at the merging area): The merging maneuvers of the merging vehicles, separately for passenger cars and heavy vehicles, are implemented in these segments , utilizing the acceleration models described in the preceding section, in addition to the lane-changing maneuvers of vehicles moving from the freeway nearside lane into the freeway far-side lane. (3) Downstream segments: In this 100-m section after the merging section, free-flow traffic conditions are simulated. (4) Lane-changing model: The lane changing model used in FMCSP is based on Gipps model (27). Lane-changing is modeled as a sequence of three steps: checking if a change is necessary and defining the type of the change, selecting the desired lane and, executing the desired lane changes if gap is acceptable.

The decision to look for a lane change depends on traffic conditions, driver's destination and behavior characteristics (e.g. from cautious to aggressive behavior). FMCSP classifies lane-changing into three types: ordinary, avoidance, and aggressive lane-changing.

- Ordinary lane-changing refers to cases in which drivers change lane well upstream of a merging section in order to increase speed, bypass a slower or heavy vehicle, response to a lane use signs or message signs, etc.
- Avoidance lane-changing component implements the lane-changing of vehicles from the freeway nearside lane, within the merging section, into the freeway far-side lane. Often vehicles change lane, especially where a two lane ramp merges to a freeway, after their first merging to avoid the delay of a second merging.
- Aggressive lane-changing component models the lane-changing behavior of drivers who move from the freeway nearside lane to the freeway far-side lane immediately before the merging section in order to avoid merging interactions.

For ordinary and avoidance lane-changing, the decision to stay or change is based on traffic conditions of both the current lane and adjacent lanes. If a vehicle has a speed lower than the driver's desired speed due to a slow vehicle in front or the maximum speed of that lane, it checks the adjacent lanes for opportunities to increase its speed. In order to choose the lane to move into, the driver first determines a set of acceptable lanes. A lane is defined as acceptable based on several criteria including lane changing regulation, lane connectivity, lane use signs, message signs, traffic conditions, and driver's desired speed.

The current version of the traffic simulation model considers parallel and taper types of acceleration lane, the length of the taper, and the convergence angle of the merging segment. The graphic interface of FMCSP displays the ramp-freeway configuration of the merging section as well as the movement of vehicles along the traffic lanes.

The validation of FMCSP was performed at microscopic and macroscopic levels using the traffic flows and lane-changing maneuvers observed at the Hamazaki-bashi and Ichinohashi merging sections, where the traffic demand exceeds the capacity resulting in upstream queues. In the microscopic analysis, trajectories from the FMSCP were compared with those from the field data. In the macroscopic analysis, the average speed, density, and volume computed using the FMCSP were compared with the values from real world traffic conditions. Further validation of the FMCSP is achieved by linking the FMCSP to a driving simulator and comparing the results against real driving behavior obtained from an instrumented vehicle [28].The results indicated that the FMCSP is capable of simulating the actual traffic conditions of congested freeway ramp merging process.

2.5 Data analysis

Heavy vehicles under all conditions take up more space than passenger cars. The Highway Capacity Manual (HCM) which has been used widely all around the world as the primary road capacity reference takes into consideration the presence of trucks by determining the passenger car equivalents, which represents the number of passenger cars that each truck is equivalent to under particular conditions [29]. It provides a constant passenger car equivalents factor of 1.5 cars for each heavy vehicle on a freeway and 2.0 cars for an arterial. There is a distinct difference between the operation of vehicles in free flow and congested flow conditions due to higher level of interaction between vehicles under congested traffic situations. One of the major limitations of the HCM approach is that it considers the same passenger car equivalents in all traffic situations. In stop-and-go traffic, heavy commercial vehicles have a much slower start-up time than passenger cars. The driving task of drivers engaged in complex maneuvers such as merging maneuvers is different from that of driving in ordinary situations [22,24]. For instance, freeway merging maneuvers are complex procedures involving lane changing, continuous acceleration, deceleration, and finally merging into a gap [30]. Nevertheless, the HCM considers the same passenger car equivalents at different freeway sections (e.g. same passenger car equivalents factor for the mainline freeway sections as well as for the merging/weaving sections). There is a growing need to quantify the actual effects of trucks on the freeway merging sections.

Extensive detector data available in this study made it possible to conduct a thorough macroscopic analysis investigating the effects of heavy commercial vehicles on the capacity of merging sections. Additional insight can also be obtained by utilizing the FMCSP which is capable of modeling the freeway merging behavior of heavy commercial vehicles described in previous sections. Presentation of these findings follows below.

Figures 2 to 5 show the results of merging capacity analysis with regards to the percentage of heavy commercial vehicles in the Ichinohashi merging section based on detectors and simulation data. For estimating the capacity of the merging sections from the detector data, the period of time is selected which is fully congested for at least 15 minutes;" i.e., queues reside on both freeway and merge approaches upstream and there is freely flowing traffic downstream. Subsequently, the capacity is simply four times of the flow rate during the fifteen minutes peak period.

The heavy vehicle percentage of the ramp stream versus capacity of the freeway nearside lane measured immediately after the merging end for both detector and simulation data are demonstrated in Figure 2. These data indicate that, as the heavy vehicle percentage of ramp traffic increases, the capacity of freeway nearside lane declines. Furthermore, the slopes of the fitted regression lines for detectors and simulation data are virtually similar.
Figure 3 displays the heavy vehicle percentage of freeway nearside lane before the merging end versus the capacity of the freeway nearside lane, measured immediately after the merging end, for both detector and simulation data. The results again indicate that as the percentage of heavy vehicles increases the capacity declines. The slopes of these fitted regression lines are also almost identical.

Additional insight can be obtained by observing the relation between the combined percentage of heavy vehicles in the ramp traffic and in the freeway nearside lane traffic versus the capacity of the freeway nearside lane for both detectors and simulation data as demonstrated in Figure 4. It is clear again that as the percentage of heavy vehicles increases, the capacity decreases. Additionally, the slopes of the fitted regression lines for the detector data and the simulation data are similar. Figure 5 shows the total percentage of heavy vehicles on the ramp and in the freeway nearside lane versus the capacity of the merging section (the maximum flow rate of the freeway nearside lane plus the maximum flow rate of the freeway far-side lane immediately after the merging end). A similar result has been obtained for the Hamazaki-bashi merging section.

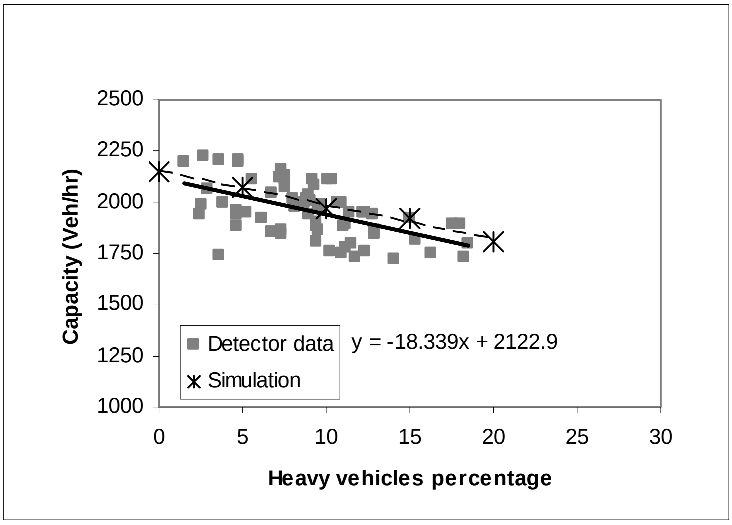

Figure 2. Heavy vehicle percentage of ramp vs. capacity of the freeway nearside lane measured immediately after the merging end.

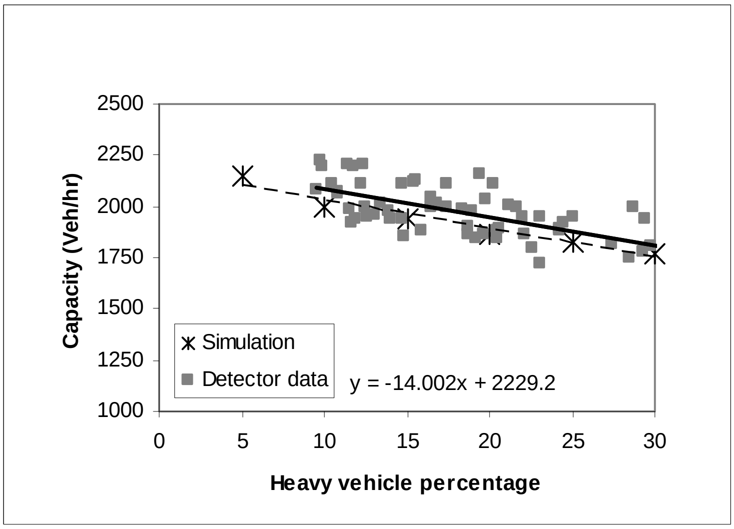

Figure 3. Heavy vehicle percentage of the freeway nearside lane before the merging end vs. capacity of the freeway nearside lane measured immediately after the merging end.

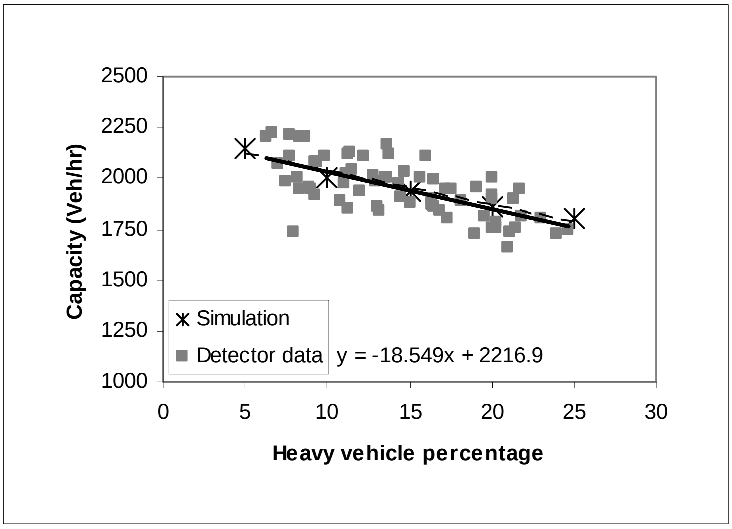

Figure 4. Combined heavy vehicle percentage of the ramp and the freeway nearside lane before the merging end vs. capacity of the freeway nearside lane measured immediately after the merging end.

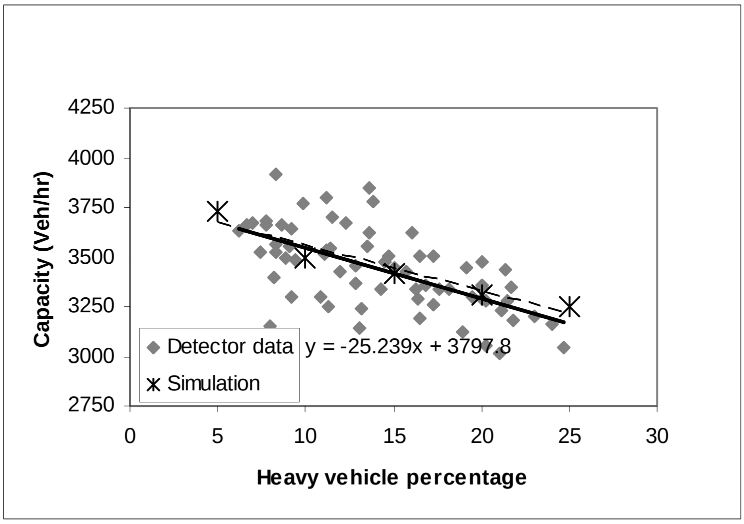

Figure 5. Heavy vehicle percentage of the ramp and the freeway nearside lane before the merging end vs. total capacity of the freeway nearside lane and the freeway far-side lane measured immediately after the merging end.

3. Development of its Operational Control Strategies

The effects of heavy commercial vehicles on the capacity of freeway merging sections were investigated utilizing detectors and micro-simulation in the preceding section. Results showed that a one percent increase in the total number of heavy vehicles results in approximately one percent reduction in the merging capacity of the freeway nearside lane (See Figure 4).

It is also important to understand the difference in the effect on the maximum flow rate of heavy commercial vehicles being in the freeway nearside lane or the freeway far-side lane. To address this, the Ichinohasi and Hamazaki-bashi merging sections were studied.

Results of detector and simulation analysis are illustrated for the Ichinohasi merging section in Figures 6 and 7.

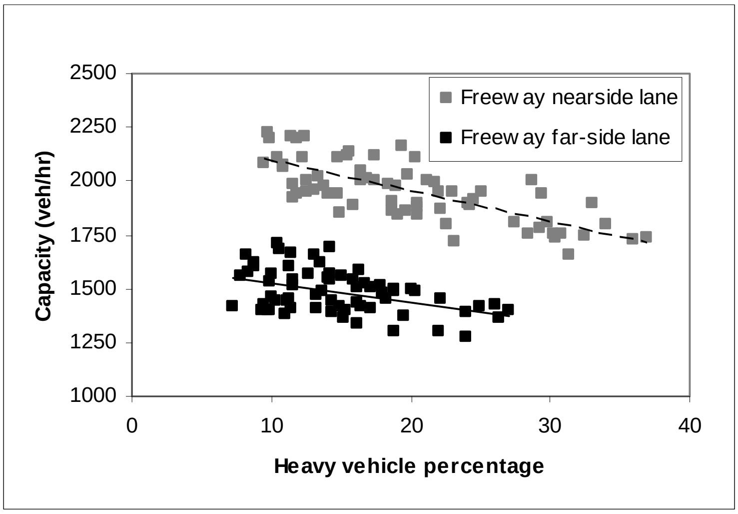

Figure 6. Heavy vehicle percentage of the freeway nearside lane and the freeway far-side lane vs. capacity based on detector data.

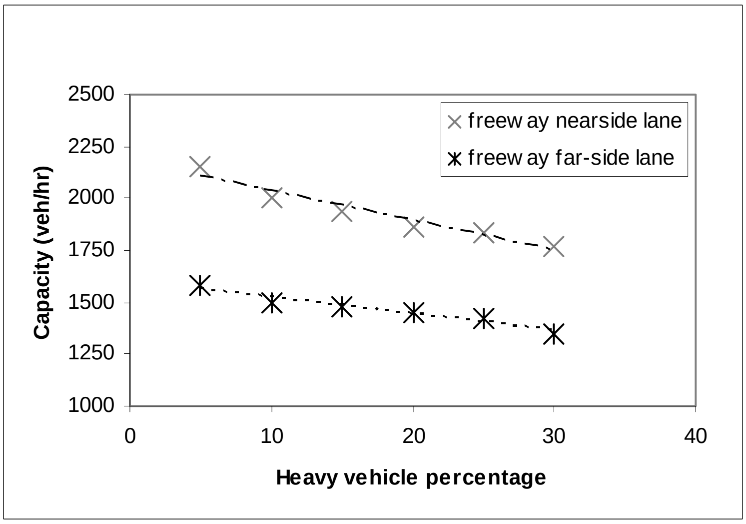

Figure 7. Heavy vehicle percentage of the freeway nearside lane and the freeway far-side lane vs. capacity based on simulation data.

These data indicate that the heavy vehicles have a larger negative impact on the maximum flow rate of the freeway nearside lane than the freeway far-side lane. In a comparative sense, the negative slope of the lines for the data of the freeway nearside lane in Figures 6 and 7 is nearly two times larger than that for the freeway far-side lane. This is due to the fact that the truck drivers in the freeway nearside lane are engaged in the merging maneuver that is of a more complex nature compared to the driving in the mainline freeway lane. Freeway merge maneuvers are complex procedures involving lane changing and continuous acceleration and deceleration. The complexity of vehicle controls and the very different handling characteristics of a large truck make its operation more difficult particularly when it is engaged in a freeway merging maneuver. Therefore, it is expected that the greatest impact in terms of a capacity reduction would occur where heavy vehicles are involved in a merging maneuver either approaching the merging area from the ramp or approaching the ramp area from the freeway nearside lane. Importantly a similar trend was observed for the Hamazaki-bashi merging section [31].

Given the above results, there is potential to increase the merging capacity by employing ITS control strategies at these bottleneck sections. One possible approach would be to utilize Variable Message Signs (VMS), installed well before the merging point, to direct the truck traffic to switch from the freeway nearside lane to the freeway far-side lane in order to improve the total throughput of the merging sections. This could also be achieved via vehicle navigation systems installed in heavy vehicles which inform truck drivers well in advance to change to the freeway far-side lane upstream of a merging section. In order to investigate the impact of these ITS control strategies, FMCSP micro-simulation is utilized. For this analysis according to Figure 6 the current average percentage of heavy vehicles for the freeway nearside lane and the freeway far-side lane are considered as 20 percent and 17 percent respectively. Table 2 summarizes the impact of the proposed freeway ramp merging control strategies.

By moving 10 percent of heavy vehicles in the freeway near side lane to the freeway far-side lane the total throughput of the merging section could be improved by 1 percent. In other words, by reducing the heavy vehicle percentage in the freeway nearside lane from 20 percent (its current average percentage) to 17.5 percent the total capacity of the freeway immediately after the merging section will improve by 1 percent. In this case, the freeway nearside lane capacity immediately after the merging point will also improve by 2.5 percent. The freeway capacity could be further improved by around 3.5 percent by moving 50 percent of the current heavy vehicles in the freeway nearside lane to the freeway far-side lane. These operational control strategies could be very effective in mitigation of traffic congestion considering the fact that most of the current congested freeways operate around only 5 percent above their existing capacity [3]. Since we are unaware of any operational experience with this approach being reported in the literature, a filed trial would be an ideal way to validate these results.
In addition, one might be interested to explore the application of the suggested ITS operations when the truck lane-use restriction policy is employed.

The FHWA handbook provided a summary of experience with truck lane-use restrictions in more than 8 states in United States [32]. This study showed that truck lane-use restriction could slightly improve the traffic operation however, it would increase merging conflicts. Various truck lane-use restrictions have also been studied utilizing micro-simulation [33, 34]. These studied indicated that operation of ramp merge and diverge areas are adversely affected by truck lane-use restriction. In another study by Garber and Gadiraju [35] it was found that truck lane-use restriction may lead to unsafe conditions at on-ramp areas with a high percentage of trucks and heavy traffic volume. Concentration of trucks on the shoulder lane could also block the visibility of signs and off-ramp exits to drivers in the inner lane [36]. These are in agreement with the suggested ITS control strategies to direct the truck traffic to switch to the freeway far-side lane in order to improve the total throughput of the merging sections as well as to increase the overall safety in the vicinity of merging areas.

Table 2. The results of ITS control strategies development.

Percentage of heavy vehicles switching from the freeway nearside lane to the freeway far- side lane	Heavy vehicle percentage of the freeway nearside lane	Flow rate of the freeway nearside lane after the merging end (veh/hr)	Heavy vehicle percentage of the freeway far-side lane	Flow rate of the freeway far-side lane after the merging end (veh/hr)	Total discharged flow rate (veh/hr)	Total capacity growth	Capacity growth of the freeway nearside lane
0%	20%	1846	17%	1467	3313	-------	-------
10%	18%	1892	19%	1451	3343	%1.00	%2.5
20%	16%	1937	21%	1435	3372	%1.78	%5.0
40%	12%	1994	25%	1406	3400	%2.62	%8.0
50%	10%	2032	27%	1394	3426	%3.4	%10.0

4. Conclusions

This study investigated the effect of heavy commercial vehicles on the capacity and overall performance of freeway ramp merging sections and sought to examine the potential of intelligent transport system control strategies for freeway merging points to mitigate traffic congestion. Comprehensive detector data and microscopic observations at two sites provided a sound and robust database for performing traffic characteristics analysis of merging sections in terms of the percentage of heavy commercial vehicles.

The traffic characteristics of heavy commercial vehicles were investigated in microscopic and macroscopic detail under congested traffic conditions. Capacity showed a negative linear relationship with the percentage of heavy commercial vehicles. The maximum flow rate of the freeway nearside lane immediately after the merging end reduced by almost one percent for every one percent increase in the percentage of heavy vehicles. The heavy vehicle percentage showed a larger negative impact on the maximum flow rate of the freeway nearside lane than for the freeway far-side lane. In a comparative sense, the negative slope of the line for the data from the freeway nearside lane was nearly two times larger than the one for the freeway far-side lane. These findings provide a constructive foundation for the development of ITS control strategies at freeway ramp merging sections.

FMCSP micro-simulation was used to investigate the benefit of deploying VMS before the merging point or alternatively relying on in-vehicle navigation systems to direct truck drivers to switch lanes from the freeway nearside to the freeway far-side in order to improve the total throughput of the merging section. It was found that by moving ten percent of the heavy vehicles to the freeway far-side lane the total throughput of the merging section could be improved by one percent. The freeway nearside lane capacity immediately after the merging point was also improved by around 3 percent. The capacity could be further improved by around four percent by moving fifty percent of the current heavy vehicles from the freeway nearside lane to the freeway far-side lane.

While this proposed strategy appears promising it is acknowledged that further research is needed to examine its operational effectiveness. To that end, further assessment and evaluation, perhaps facilitated through a field trial, would be advantageous.

References

[1] The Freight Task in Victoria, A commentary on Commodity, Corridor and Future Growth Forecasts, Department of Infrastructure, Melbourne, Victoria, 2002.
[2] Federal Highway Administration (2004): "Traffic Congestion and Reliability: Linking Solutions to Problems". Prepared by Cambridge Systematics, Inc.
[3] M. Kuwahara (1991) Transport in the Tokyo Metropolitan Region. Journal of Built Environment on the subject of Transport in World Cities, Vol 17, No.2. 1991.11.
[4] Beakey, J. 1938. Acceleration and deceleration characteristics of private passenger vehicles. Proceedings of the 18th Highway Research Board Annual Meeting, Washington, D.C.:81-89.
[5] Hess, J.W. 1963. Capacities and characteristics of ramp-freeway connections. HRR 27.
[6] Hess, J.W. 1965. Ramp freeway terminal operation as related to freeway lane volume distribution and adjacent ramp influence. HRR 99.
[7] Pinnell,C. 1960. Traffic behavior and freeway ramp design. Journal of the highway design proceeding of the American Society of Civil Engineering.
[8] Hess, J.W., "Traffic Operation in Urban Weaving Areas." Bureau of Public Roads (1963 data, in preparation for publication).
[9] Chang, G., YM, C., 1991. An empirical investigation of macroscopic lane changing characteristics on uncongested multilane freeways. Transportation research Journal, Vol. 25A.
[10] Daganzo, C., 1979. Estimation of gap acceptance parameters within and across the population from direct roadside observation. Transportation research Journal, Vol. 15B.
[11] Drew, D., LaMotte, L., Wattleworth, J., 1967. Gap acceptance in the freeway merging process. Highway research record 1967.
[12] Kita, H., 1993. Effects of merging lane length on the merging behavior at expressway on-ramps. International Symposium of Traffic and Transportation Theory, C. Daganzo (ed.), Elsevier Science & Pergoman Pub.: 37-51.

[13] Kita, H., 1998. A merging-give way interaction model of cars in a merging section: A game theoretic analysis. Transportation research Journal, Vol. 33A.
[14] Makigami, Y., Adachi, Y., Sueda, M., 1988. Merging lane length for expressway improvement plan in Japan. Journal of transportation engineering, Vol. 114, No. 6.
[15] Minderhoud, MM; Hansen, IA (2001), A microscopic simulation study after freight lanes near merging areas, 8th World Congress on Intelligent Transport Systems, Australia.
[16] Kenny, B; Kwan, A; Morrall, J (2000), Design and operational considerations to accommodate long combination vehicles and log haul trucks on rural highways in Alberta, Canada, 2nd International Symposium on Highway Geometric Design, Germany.
[17] Tom, GKJ; Fong, HK (1997), A case study of truck merging operation at selected freeway on-ramp locations in California, Report No: FHWA/CA/TO-96/15; Report No. 51-623260; California Department of Transportation.
[18] Miaou, S-P., P.S. Hu, T. Wright, A.K. Rathi, and S.C. Davis.1992. Relationship Between Truck Accidents and Highway Geometric Design: A Poisson Regression Approach. T*ransportation Research Record* 1376:10–18.
[19] Awad, W. and B.N. Janson. 1997. Prediction Models for Truck Accidents at Freeway Ramps in Washington State Using Regression and AI Techniques, presented at the 77th Annual Meeting of the Transportation Research Board, Washington, DC.
[20] Zaloshnja, E and T.R. Miller (2004), Costs of large truck-involved crashes in the United States, Accident Analysis and Prevention, 36, 801-808.
[21] Sarvi M, Ceder A, Kuwahara M, Morita H (2001) "Macroscopic study of freeway ramp merging phenomena observed in traffic congestion." Journal of eastern Asia, society of Transportation engineering, EAST 4(2), 185-200.
[22] Sarvi M, Ceder A, Kuwahara M. (2002) Modeling of freeway ramp merging process observed during traffic congestion. In: Taylor, M. (Ed.) Transportation and Traffic Theory, Elsevier, 483-502.
[23] Herman, R and Rothery, RW (1963). Car following and steady state flow. Proceeding of the second International symposium on the theory of road and traffic flow, London, United Kingdom.
[24] Sarvi M, Ceder A, Kuwahara M. (2005) "Freeway ramp merging process observed in congested traffic: Lag vehicle acceleration model". In: Mahmassani, H. (Ed.) Transportation and Traffic Theory, Elsevier, 303-321.
[25] Newell, GF (1999). A simplified car-following theory: A lower order model. Institute of Transportation Studies, University of California at Berkeley, Research Report UCB-ITS- RR-99-1.
[26] Sarvi M. Ceder, A., Kuwahara, M. (2005) "Development of a micro-simulation program to study freeway ramp merging process in congested traffic condition" Submitted for publication in the Journal of IEEE Transaction on Intelligent Transportation.
[27] Gipps, P.G. (1986) "A Model for the Structure of Lane-Changing Decisions" Transport. Res. 20B, pp. 107–120.
[28] Sarvi, M., Kuwahara, M Ceder, A. (2004). "A study on freeway ramp merging phenomena in congested traffic situation by traffic simulation combined with driving simulator". Journal of computer-aided civil and infrastructure engineering 19, 351-363.
[29] Highway Capacity Manual, U.S. Government Printing Office, Washington DC 2000.
[30] Michaels and RM, Fazio, J (1989). Driver behavior model of merging. TRR 1233.

[31] Sarvi, M (2000). Freeway ramp merging phenomena observed in traffic congestion. Ph.D. dissertation, University of Tokyo.
[32] FHWA, Freeway Management and Operations Handbook, Final Report, September 2003, Chapter 8.
[33] Cate, MA. and Urbanik T. (2004). “Another view of truck lane restrictions”. Transportation Research Record 1867, TRB, pp. 19-24.
[34] Gan, A. and Jo, S. (2003). “Operational performance models for truck-lane restrictions”. Final report, Florida International University, Miami, FL.
[35] Garber N.J and Gadiraju, R. (1990). “Effect of truck strategies on traffic flow and safety on multilane highways” Transportation Research Record 1256, TRB, pp. 49-54.
[36] Carvel, J.D., Balke, K., Ullman, J., Fitzpatrick, K., Nowlin, L., and Brehmer, C. (1997). “Freeway Management Handbook”, TTI, College Station, TX.