Improving the control strategies of freeway merging points using modeling and simulation approach

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Summary

The main objective of this study is to investigate traffic behavior and characteristics during the merging process under congested situation to design a safer and less congested merging points as well as a more efficient control at these bottleneck sections. In Tokyo Metropolitan Expressway (MEX), as in other freeways, traffic congestion frequently occurs at merging bottleneck sections especially under heavy traffic demand. Metropolitan expressway public corporation generally applies different empirical strategies such as closure of one lane or installation of post cone to increase the flow rate and decrease the accident rate at the merging sections. However, these strategies do not rely on any behavioral characteristic of the merging traffic under congested condition and its relation with geometric design of the merging segments. There have been only a few research publications about the traffic behavior and characteristics in these situations. Based on extensive macroscopic and microscopic study, a behavioral model has been developed for these situations. In addition and based on the behavioral model as an evaluation tool, a multi-purpose simulation program FMCSP (Freeway Merging Capacity Simulation Program) has been developed. The outcome of the behavioral and simulation models is applied to ITS in order to develop variety of strategies for safer and less congested freeway merging sections. Also in this research a link between FMCSP and a certain DS (Driving Simulator) is made to experiment the effect of geometric design, lane marking, VMS, etc on the driving behavior. The conceptual framework to approach these issues is illustrated in Figure 1.

Introduction

The freeway on-ramp merging process has been studied since the 1940's. Research on driver behavior during on-ramp merging process and the effect of ramp geometric design and traffic characteristics was made while focusing on free flow merging when speed of vehicles ranged between 50-100 km/h (1). Only a few research are examining the driver behavior, geometric design, and traffic characteristics under heavy traffic when the ramp drivers make continuous stops before merging or force a merge into a stop-and-go freeway flow. Traffic condition in which the demand exceeds the capacity might induce a special driver behavior. However, due to the lack of sufficient data in congested situation, affect of those traffic and geometric characteristics on capacity and traffic behavior were not clearly addressed. This is the purpose of this study to focus on the merging process under congested freeway traffic condition.

Motivations and objectives

Variety of strategies can be applied to improve the traffic flow rate and safety at the merging sections. It is possible then to use ITS facilities such as VMS (variable message sign) or navigation systems prior to the merging section to inform the drivers and guide the traffic. Other strategies like closure lane or installing post cone need experimental data, which is difficult to obtain because of the possible high, cost and risk involved. A substitute for the real examination and evaluation of such strategies can be simulation experiments which simulate actual traffic scenarios and make it possible to evaluate the effectiveness of the strategies. This is one objective of the research. Another objective is to make a link between the simulation, FMCSP, and a driver simulator, DS, to examine a variety of strategies and studying of the geometric design effects on the freeway merging sections capacity. For this purpose, FMCSP has been developed for simulating actual traffic condition for DS. The outcome of the DS experiences could be applied directly to FMCSP as a feedback to make it more accurate and reliable. In addition, the model can be used for ITS applications such as VMS to be installed before the merging point to direct the traffic, Navigation systems to inform the driver when to switch lanes or what to expect downstream), AHS (Automatic Highway System), Convoy driving systems, and Traffic control centers about how to establish a smart strategy (lane closure scenarios, the optimal distance for the lane closure, activating a warning system in a stormy weather or in an accident case, etc). In this paper, the developed FMSCP model is employed to compare the capacities between an ordinary and AHS freeway merging sections.

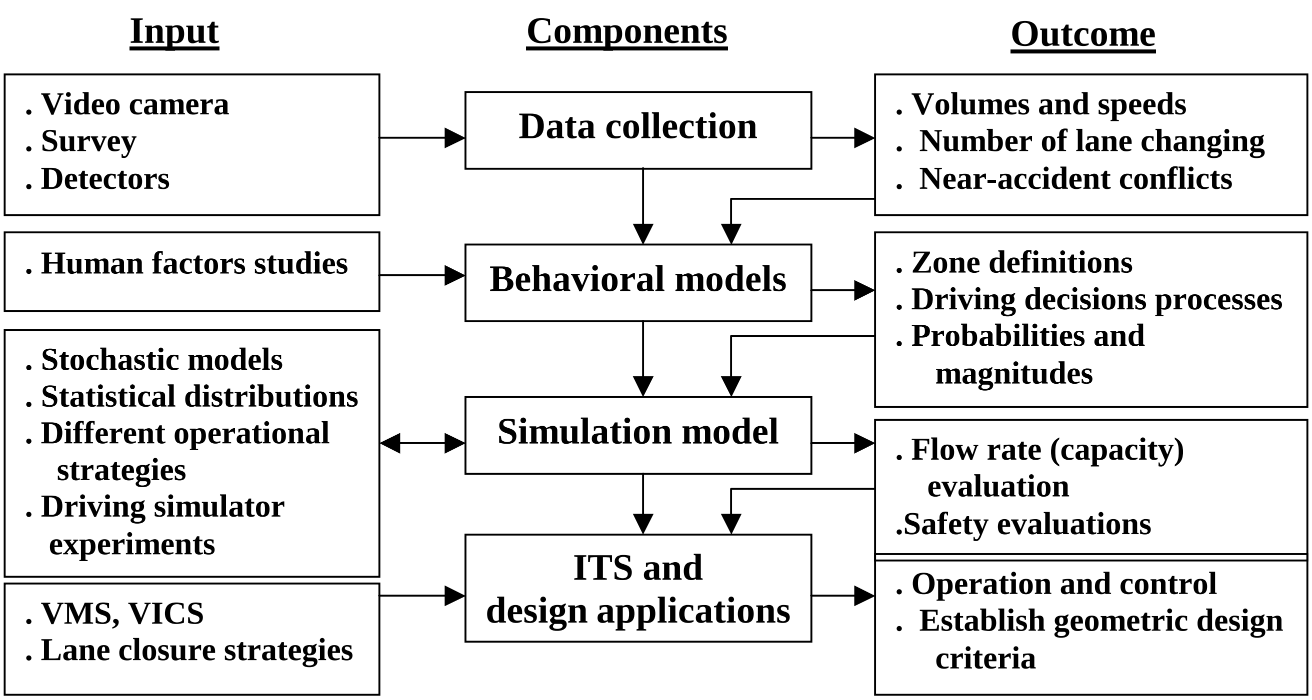

Figure 1. Conceptual framework of the study

Modeling

Vehicle interaction and traffic behavior

<u>Driver's decision process</u>

There are different drivers tasks and decision-making processes under free-flow than congested-flow conditions while approaching freeway merging points. Three zones are established to explain the driver decision-making process in these situations as it is shown in Figure 2. They includes:

Ramp zone one (preliminary zone): A decision about how to arrive to zone two (from lane one or two)?,
Ramp zone two (merging zone): A decision about between which two vehicles to merge (to be inserted)?,
Ramp zone three (downstream zone): A decision about in what distance and speed to follow the vehicle in front?
Freeway zone one (preliminary zone): Same as ramp zone one,
Freeway zone two (merging zone): A decision about to which vehicle oncoming from ramp to allow merging?,
Freeway zone three (downstream zone): Same as ramp zone three.
The first driver decision is highly affected by the surrounding traffic situation such as traffic volume in the two lanes, traffic flow speed, desirable gap, drivers attitude, vehicle type, drivers familiarity with the area, etc. The second decision about a proper gap searching and accepting has been extensively studied in the free flow merging condition. In the congested flow based on extensive macroscopic study and observations in the Tokyo Metropolitan expressway (2) it was found that drivers mostly merge one by one at the terminus part of merging section. The third driver decision is related to the known car-following behavior and will not be dealt in this paper.

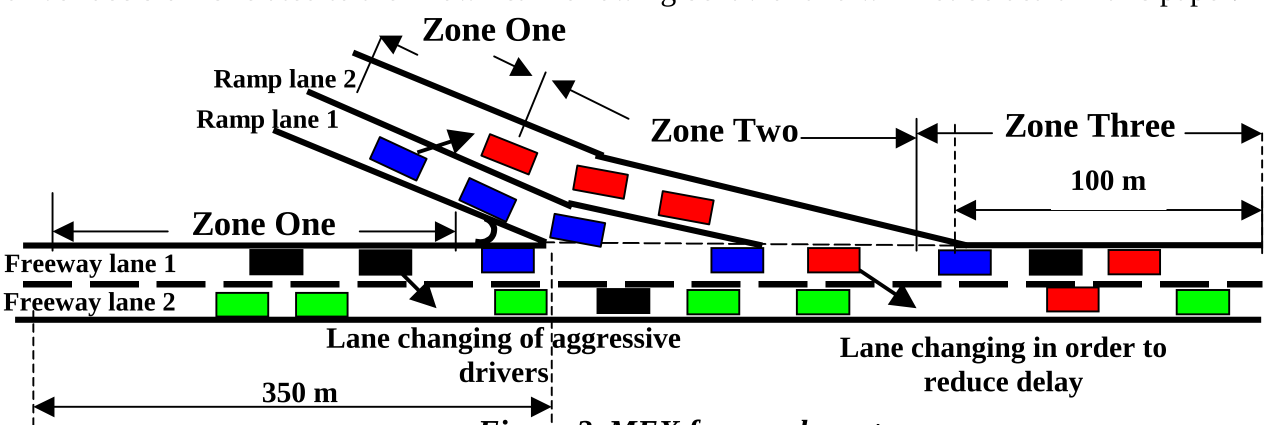

Figure 2. MEX freeway layout

<u>Vehicles interactions and lane changing behavior</u>

The possible traffic interaction between vehicles approaching and engaging the merging area under congested traffic condition is described in Table 1. It is based on comprehensive observations (2). Table 1 includes lane changing in zone one before engaging the merging section, merging at zone two, lane changing within zone two, and car following behavior between vehicles. For example, driver **i** at freeway lane one may interact with driver **j** in freeway lane two by changing lane to the adjusted freeway lane. This lane changing could be achieved either in zone one or two. Research on lane changing behavior has been focused on gap acceptance behavior and its application. In this paper, lane-changing behavior in the merging area under congested situation has been studied at the macroscopic (not individual vehicle) level of the MEX. Two types of lane changing behavior are observed frequently in the merging sections. In zone one, while trying to avoid merging interactions, aggressive drivers forcing their vehicles into the freeway/ramp lane two. In zone two, while trying to avoid more delay for a second merging some drivers forcing their vehicles into freeway lane two. These lane-changing behaviors effect the flow rate at the merging section, e.g. decrease the flow rate at the freeway in lane two and increase the flow rate at the ramp.

Table1. The possible types of vehicle interactions.

		Freeway		Ramp	
		Lane 1	**Lane 2**	**Lane 1**	**Lane 2**
Freeway	**Lane 1**	Car following	Lane changing	Slow down to provide right of way	Slow down to provide right of way
	Lane 2	None	Car following	None	None
Ramp	**Lane 1**	Merging	Almost none	Car following	Lane changing
	Lane 2	Merging	Almost none	Almost none	Car following

FMCSP: a simulation model

Outline of FMCSP

A periodic scanning method at intervals of 0.05 seconds is used for this simulation model. In FMCSP the study areas are not only the merging sections but also the upstream/downstream sections. These sections are treated as three types with different characteristics (see Figure 2). FMCSP considers the following: (1) Preliminary segments (Ramp and freeway lanes 1 and 2 prior to the merging point): the purpose of these segments is to generate vehicles at the most upstream end, and to form platoons while traveling through the 350m segment. At the beginning of freeway segment, vehicles are dynamically generated based on travel time on shoulder and median lane of the freeway. Therefore, since travel time of vehicles on the freeway shoulder lane is more than the median lane (because of the merging maneuver), more vehicles are generated on this lane. Moreover, the size and acceleration/deceleration performances of each vehicle such as truck and light vehicle are simulated by FMCSP. Each driver has a desired speed, which follows the normal distribution. The parameters of this distribution are provided when vehicles are generated. (2) Merging segment (Ramp and freeway lanes at the merging area): The merging maneuvers of the merging vehicles are implemented in these segments in addition to the lane changing situations of the freeway shoulder lane vehicles into the freeway median lane. The 10 meters segment between zones two and three is defined as the terminal segment in which non merging vehicles are forced to merge. (3) Downstream segments (Freeway lanes at zone three): In this 100m-section, free flow traffic conditions after the merging section, are simulated. (4) Aggressive driver’s lane changing model: The lane changing behavior of the aggressive drivers in the freeway shoulder lane is implemented by this model before the merging section. The term aggressive drivers implicate those in the freeway shoulder lane who then change lane immediately before the merging section to avoid merging interactions. Based on direct observation and video data collections, this lane changing behaviors decreased the flow rate of the freeway median lane and therefore affects the total output flow rate of the freeway.(5) Avoidance lane changing model: The lane changing of vehicles from the freeway shoulder lane (within the merging section) into the freeway median lane is implemented by this model. Often vehicles change their lane, especially where the two ramp lanes merge, after their first merging in order to avoid more delay for the second merging situation. The current version of the traffic simulation model considers the parallel and taper types of acceleration lane, the length of the taper as well as the divergence angel of the merging segment. In addition, the output of FMCSP during the simulation run is saved in text files at the end of simulation for future analysis. By the aid of the graphic interface of FMCSP the ramp-freeway configuration of the merging section as well as the movement of vehicles along the traffic lanes are displayed. The validation of model has been performed at microscopic and macroscopic levels using the observation flow, and lane changing maneuver for two congested merging sections in MEX, where the traffic demand exceeded the capacity resulting in formation of upstream queues (see Table 2). For validation of FMCSP two lane changing maneuvers, one before the merging section and second within the merging section with five discharged volumes as well as time trajectories of vehicles were compared with the observation. The simulated values were found to fit well the observed ones(3).

ITS application of FMCSP

One possible application of FMCSP is to evaluate the configurations of an Automated Highway System (AHS). The AHS intends to improve the safety and to increase the efficiency of freeways. It also intends to further raise our quality of life through the transportation infrastructure by reducing the time spent in traffic congestion and decreasing the number and severity of road accidents. However, theses and other benefits can not be realized without an effective traffic merging control process. If this process is not properly designed and managed, bottlenecking could occur at the merging areas and the resulting congestion could spill-back onto the mainline of the AHS. To avoid these problems the merging vehicles must be able to coordinate their speeds and synchronize movements together with the mainline traffic through a direct communication and/or infrastructure systems enable to facilitate a smooth maneuver into appropriate sized gaps. In order to demonstrate capability of the FMCSP for ITS application a case study was carried out for comparing the capacity of ordinary freeway merging section with the capacity of an AHS freeway. For this purpose, the merging capacity of Ichinohashi interchange at MEX is compared to an AHS freeway with similar geometric design and traffic conditions. In this set of simulations, the minimum headway of an AHS platoon was set to 1.6 sec while it was set to 1.77 sec for the ordinary case. The simulation result is shown in Table 2. The simulation results show that the discharged volumes of the freeway shoulder lane, the freeway median lane, and the ramp lane fit well with the observed volumes. In addition the comparison between the merging capacity of an ordinary section with AHS one reveal that the capacity of 4191 pcu/hr/2-lane in the AHS section is about 14 percent higher than the capacity of ordinary section.

Table 2. Comparison between ordinary and AHS merging capacity.

	Freeway Shoulder lane volume (pcu/hr)	**Freeway median lane volume (pcu/hr)**	**Ramp lane volume (pcu/hr)**	**Total discharged volume (pcu/hr/2lane)**
Observed values of Ichinohashi ordinary merging section	**945**	**1749**	**1010**	**3704**
Simulation values of Ichinohasi ordinary merging section	**997**	**1667**	**1001**	**3665**
Simulation values of Ichinohasi AHS merging section	**1056**	**2079**	**1056**	**4191**

A link between FMCSP and a driving simulator

Integration approach

To gain a clear understanding of previous research deficiencies and to search for possible directions of future improvements related literature has been reviewed. Unfortunately, it appeared that almost no related study could be found in literature addressing the freeway ramp merging phenomena study via the DS, especially under congested situation. Software and hardware are the most important components in successful development and performance of the DS experiments. FMCSP has been extensively calibrated, improved, and modified to become capable of simulating the actual traffic scenarios of driving simulator. Additionally, the driving simulator that was originally designed for driving in the straight freeway segments was adjusted to become appropriately suited for simulating the virtual driving at freeway ramp merging scenarios. Due to the sophisticated nature of this problem, performing a pilot study to investigate the feasibility and deficiencies of combined system of FMCSP and DS is desired before major efforts are undertaken. Therefore, a pilot study has been conducted to detect the potential deficiencies, and potential problems of combined system of FMCSP and DS. Finally, the main experiment has been done in order to collect the required data. At last, in order to have a clearer perspective of DS driver's behavior, two participants of DS experiments were asked to drive with an experimental car at Ichinohasi merging section.

Outline of the driving simulator

The configuration of the driving simulator system used in this study as well as the flow of data and test procedure is illustrated in Figure (3-a). Computer graphics of virtual space created by a workstation (Onyx Reality Station) are displayed on a 120-inch screen. Response of the subject to the image on the screen is input via the driver's seat. Increase of accelerator or brake use is input in 1 % increments of acceleration or deceleration rates, respectively. The information input through the driver's seat is used to control the creation of following computer graphics. The speedometer at the driver's seat indicates the velocity calculated based on the rate at which computer graphics are created. In the calculation of vehicle velocity, the effects of air resistance, road surface resistance and the gravity acceleration acting on the vehicle according to the vertical alignment are considered. Running noise of the vehicle is also the output. At present, however, no noise variations according to the speed or roadside condition are reproduced.

Data collection and experimental operation

In this research, initially it is planned to collect the driving behavior data of about 12 persons while they are driving in the driving simulator. For this purpose each of the 12 drivers, who were mostly students, were asked to drive in the driving simulator. The procedure of experiments and data collections for each participant is described as follows:

1) Due to the different nature of DS and real world driving environment, prior to run of the final experiments, each participant was asked to drive in the driving simulator in an ordinary section of the highway at a high-speed as much as he/she wanted. The main objective of this driving exercise was that drivers become familiar with the operation and control nature of DS driving. 2) Furthermore, during the second step each driver was asked to drive under main scenario and drive from the on-ramp merging into the freeway stream when the traffic situation was congested. Each driver was allowed to drive from the section almost 350 meters prior to the merge end. 3) Finally, after sufficient driving exercise in the driving simulator under main scenario, namely merging from on-ramp to freeway stream under congested traffic situation, each participate was asked to drive under the same aforementioned scenario for three times while the

required data was collected during the experiments. Figure 3-b is an image of the graphical display of the driving simulator.

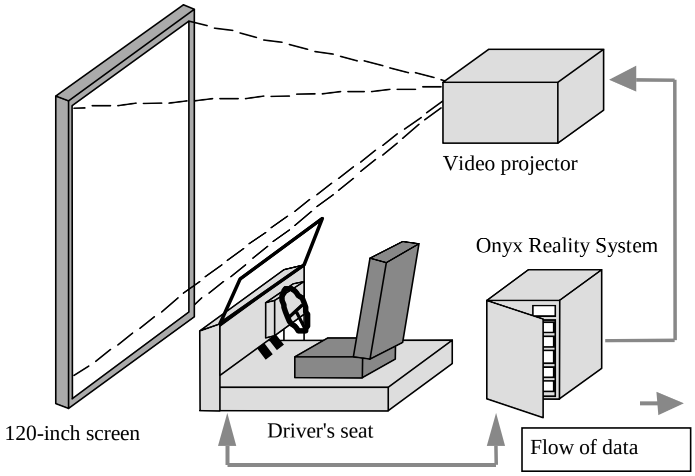

Figure 3-a

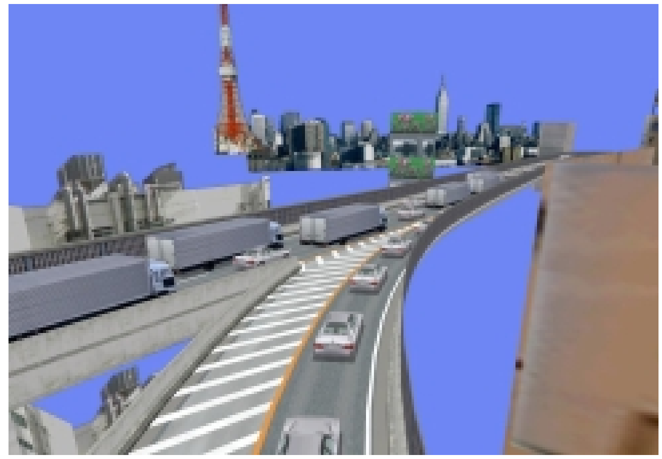

Figure 3-b

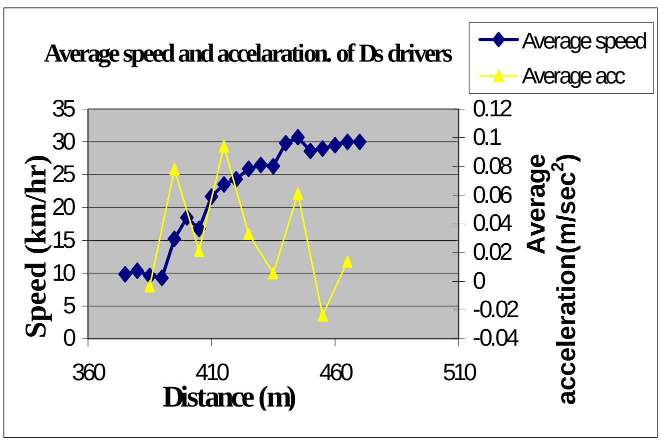

Figure 3-c

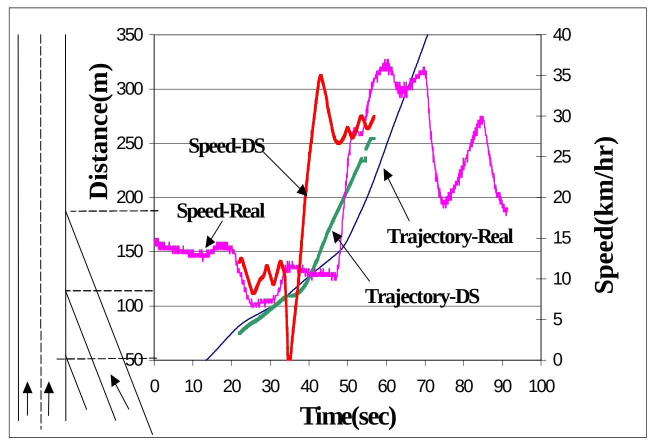

Figure 3-d

General behavior of the ramp drivers in the acceleration lane of DS

A ramp driver in the acceleration lane must perform many different tasks in a timesharing mode before merging onto the freeway stream. Interaction with the freeway vehicles and variability with drivers makes the observed behavior different from driver to driver. The outcomes of these variations depict the fundamental aspects of entrance ramp operations. The following is a discussion of fundamental phenomena of the merging operations obtained from DS data analysis.

The primary data of interest was the speed of vehicles traveling in the acceleration lane and entering the freeway. These speeds provide a vehicle speed change profile during transition, indicating where and with what magnitude vehicles were accelerating or decelerating, the speed at which vehicles were entering the freeway along the merging area. Speed data was obtained from the output file of DS experiments in 0.05-second interval. In order to have appropriate perspective of driver behavior the average speed profile of twelve drivers during DS experiments was calculated. Figure (3-c) shows calculated ramp vehicle average speed and acceleration profiles based on distance from ten meters prior to the merge end. Figure (3-d) demonstrates a sample of time trajectory, and speed profile of DS and experimental car of a driver participated in this study. The time trajectories and speed profile shown in Figure (3-d) indicate that, the driving behavior of DS and experimental car drivers are identical. The driver in both DS and car experiment test keeps a constant speed while he is in the queue up to the nearly the merge end. After he reaches almost the end of zebra marking, at that time, as the leader of the ramp vehicles platoon he will decelerate in order to adjust his speed with the corresponding freeway lag and leader vehicles. Thereafter the ramp driver will accelerate to join the freeway stream either by making a force merge or by accommodating with the corresponding freeway lag vehicle. Initially the ramp vehicle will decelerate once the driver enters the freeway stream, this is because the driver starts to adjust his speed considering the speed of the freeway leader.

Conclusions and future research

Comprehensive traffic data was collected via a video system, and surveys at several merging sections of Tokyo Metropolitan Expressway (MEX) to investigate and develop a model of the traffic behavior and characteristics on a congested freeway. In addition, the capacity of the merging segments (discharged flow rate at the bottleneck) were observed using vehicle detectors in eight merging sections of the MEX. This data includes the examination of the effect of the geometric design and traffic characteristic on the merging capacity.

A multi-purpose simulation model for simulating actual situations of the freeway merging sections under congested traffic conditions was developed and validated using two interchanges of MEX. The simulated values of discharged volumes are found consistent with the observed traffic volumes. This simulation model can take into account the difference between parallel and taper acceleration type of merging lanes as well as convergence angel of the merging section.

The outcome of these two models (i.e. behavioral and simulation models) can be used as a fundamental tool for developing a variety of strategies for alleviating congestion at merging points as well as increasing their safety. This tool can be then utilized for proper ITS applications such as VMS and VICS. As an example of capability of FMCSP simulation model, a comparison between the merging capacity of ordinary freeway and an AHS freeway was made. The result of this comparison is that the AHS freeway provides 14% more capacity at the merging points than an ordinary freeway.

In addition, an attempt is made to link the FMCSP model with a Driver Simulator (DS) to examine different strategies (e.g. using VMS, VICS) as well as different geometric design (e.g. zebra marking, lateral clearance) and their effect on an average driving behavior. The outcome of these experiments is applied to the FMCSP model as a feedback in order to make it more accurate and reliable. The results of DS study evidenced that not only the FMCSP is capable to simulate the actual traffic condition of the freeway ramp merging process under congested situation but also DS is quite a promising substitution tool for studying of complicate driving behavior during the freeway ramp merging maneuver.

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