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Freeway Ramp Merging Phenomena in Congested Traffic Using Simulation Combined with a Driving Simulator

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Abstract: *Freeway ramp merging was studied under congested traffic conditions using a driving simulator (DS). First, the results of extensive macroscopic and microscopic studies were used to establish a model for the behavior of merging drivers. 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 design and flow condition. Next, a DS was developed to be used in conjunction with the FMCSP. The DS and simulation were combined by replacing one vehicle in the FMCSP by the DS. A pilot study was then undertaken to test for deficiencies in the combined system. Finally, the main DS experiment was performed using 12 male drivers. Driving behavior data were collected while each participant drove in the DS through the Ichinohashi merging section. In addition, two participants of the DS experiments drove an instrumented car through the real Ichinohashi merging section. The driving behavior data from the DS, instrumented car, and observation of drivers were compared to investigate the behavior of DS driver and examine differences between the behavior of drivers using simulators and those in the real world. The results indicated that the FMCSP is capable of simulating the actual traffic conditions of congested freeway ramp merging processes, and that the insertion into a simulation of a vehicle controlled by a DS is a promising tool for the study of complicated ramp merging phenomena.*

1 INTRODUCTION

Carmakers, suppliers, and transport research laboratories commonly employ driving simulators in research and development. Driving simulators are well established as training tools, and are becoming an essential component in new vehicle research and development as well as an increasingly useful tool in traffic and transportation

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research. However, the use of driving simulators in traffic and transportation studies remains a novel concept, despite its rapid increase since the 1990s. Driving simulators have been primarily used to study the safety aspect of traffic and transportation engineering. No research has been done that is relevant to the application of driving simulators to the problem of freeway ramp merging. The present work represents the first attempt to utilize a driving simulator to study freeway ramp merging phenomena.

A variety of strategies can be applied to improve the traffic flow rate and safety at merging sections. One possibility is to use ITS (Intelligent Transport System) facilities such as VMS (variable message sign) or navigation systems ahead of the merging section to inform drivers and guide traffic. Other strategies such as lane closure or post cone installation require experimental data for their implementation, which in most cases is difficult to obtain because of the risks and high costs involved in data collection (Sarvi, 2000a). An alternative to the examination and evaluation of the real traffic conditions is to use simulation experiments to mimic actual traffic scenarios. Using this approach, simulation results are used to test the effectiveness of traffic control strategies. This study describes the methodology for linking a driving simulator (DS) into the Freeway Merging Capacity Simulation Program (FMCSP). This work is undertaken to compare the behavior of DS drivers with that of drivers in the real world as they carry out freeway ramp merging maneuvers under congested traffic conditions.

A set of detailed activities were defined and followed to achieve the general elements included in this study. Figure 1 presents a conceptual flowchart of these activities.

2 MODELING

2.1 Vehicle interaction and traffic behavior

2.1.1 The decision process of drivers. The tasks and decision-making processes required of drivers approaching a freeway merging point differ between free-flow conditions and congested-flow conditions. A comprehensive traffic survey and on-site observation have shown that the decision-making process of drivers in merging situations can be divided into three zones, as shown in Figure 2 (Sarvi, 2000a, Sarvi et al., 2001). The decisions required in each zone can be expressed as follows.

1. Ramp Zone 1 (preliminary zone): A decision about how to arrive at Zone 2 (from lane one or two),
2. Ramp Zone 2 (merging zone): A decision about which two vehicles to merge between,
3. Ramp Zone 3 (downstream zone): A decision about at what distance and speed to follow the vehicle in front,
4. Freeway Zone 1 (preliminary zone): Same as ramp Zone 1,
5. Freeway Zone 2 (merging zone): A decision as to which vehicle from the ramp should be permitted to merge,
6. Freeway Zone 3 (downstream zone): Same as ramp Zone 3.

The first decision that a driver must make is greatly affected by the surrounding traffic situation (e.g., traffic volume in the two lanes, traffic flow speed, desirable gap) and by the circumstances of the particular driver (e.g., attitude, vehicle type, familiarity with the area). The second decision, which involves the ramp driver

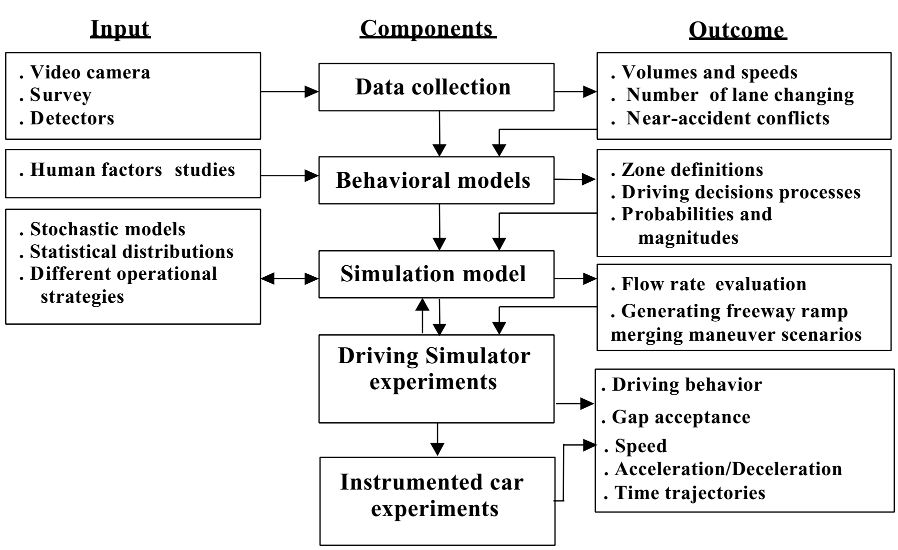


Fig. 1. Conceptual flowchart for this study.

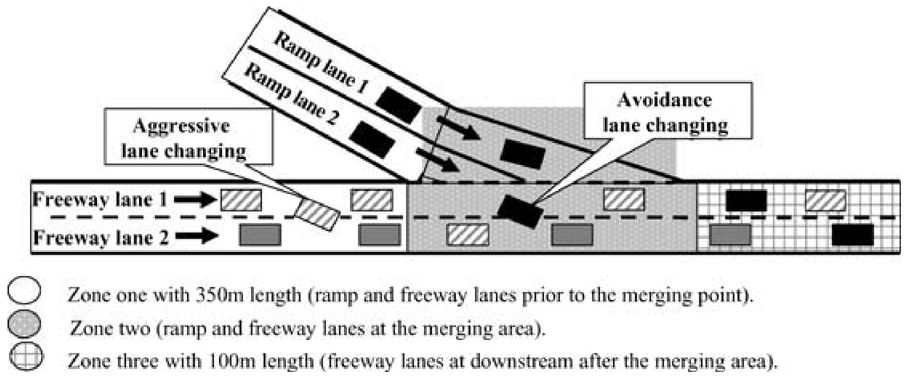


Fig. 2. Zone specifications during freeway ramp merging maneuver.

searching for and accepting a suitable gap, has been extensively studied for the free-flow merging condition (Drew et al., 1967; Daganzo, 1979; Makigami et al., 1988; Chang and Ym, 1991; Kita, 1993, 1998; Ahmed et al., 1996, Ahmad, 1999; Kurian, 2000). The gap searching and acceptance maneuvers commonly observed under free-flow conditions do not occur under heavy traffic flow conditions, according to a comprehensive macroscopic study and observations of the Tokyo Metropolitan Expressway (MEX) (Sarvi et al., 1999, 2001.). These macroscopic studies found no significant correlation between the acceleration lane length and the maximum flow rate in the merging sections (See Figure 3). Heavy traffic conditions also lead to squeeze merging at the end of the merging section. Here, we define this type of merging as **zip merging**, which refers to the situation where vehicles from the ramp and freeway shoulder lane merge together one by one regardless of the available gap. Observations at the Ichinohashi and Hamazaki-bashi merging sections under congested traffic flow found more than 97% of merging maneuvers to be of the zip-merging type. Therefore, in this study the gap searching and acceptance maneuver will not be addressed. The third decision, related to car-following behavior, will be discussed later in this article. Sketches of Hamazaki-bashi and Ichinohashi merging sections are depicted in Figures 4a and b.

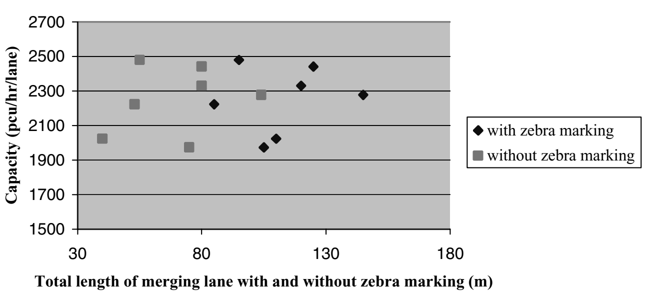
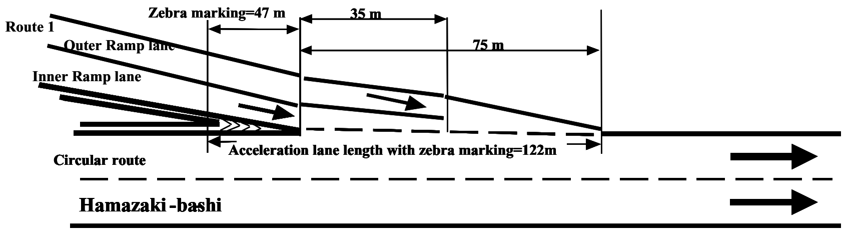


Fig. 3. Relationship between total length of merging lane with and without zebra marking and merging capacity.

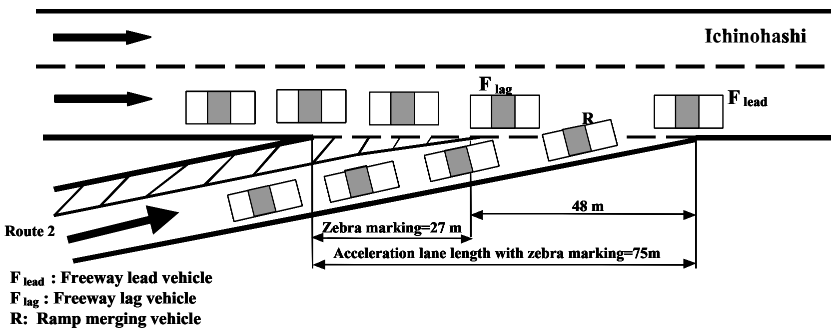
2.1.2 Vehicle interactions and lane-changing behavior. Table 1 lists the possible interactions between vehicles approaching and engaging the merging area under congested traffic conditions, as established by comprehensive observations (Sarvi, 2000a). These interactions include lane changing in Zone 1 before engaging the merging section, merging at Zone 2, lane changing within Zone 2, and car-following behavior between vehicles. For example, driver **i** in freeway lane 1 (row 1) interacts with driver **j** in ramp lane 1 (column 3) by slowing down and provides a gap that is sufficient for the ramp vehicle to merge. Conversely, driver **i** in ramp lane 1 (row 3) interacts with driver **j** in freeway lane 1 (column 1) by forcing a merge in order to merge as early as possible. Research on lane-changing behavior has focused on gap-acceptance behavior and its applications. In this study, lane-changing behavior in the merging area under congested traffic conditions was investigated at the macroscopic (not individual vehicle) level (Sarvi et al., 2001). Two types of lane-changing behavior were frequently observed in the merging sections. In Zone 1, aggressive drivers forced their vehicles onto the freeway/ramp lane 2 in order to avoid merging interactions. In Zone 2, some drivers forced their vehicles into the freeway lane 2 in order to avoid the delay of a second merging. These lane-changing maneuvers affected the flow rate at the merging section, usually causing a decrease in the flow rate in freeway lane 2 and an increase in the flow rate of the ramp. FMCSP explicitly modeled both these lane-changing maneuvers.

2.2 Methodologies for modeling ramp driver acceleration–deceleration behavior

Freeway merge maneuvers are complex procedures involving various steps, for example, a lane change,



(a)



(b)

Fig. 4. (a) Sketch of Hamazaki-bashi merging section. (b) Sketch of Ichinohashi merging section.

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. Ramp drivers must process the roadway and traffic information and translate that information into decisions regarding their speed and position. 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 (see Figure 4b), and the spacing between the ramp vehicle and the freeway lead and lag vehicles. This investigation was undertaken with a view to develop 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 to collect a wide range of information. Comprehensive traffic surveys were conducted at two entrance ramps in the MEX (Hamazaki-bashi with parallel type acceleration lane and Ichinohashi with taper type acceleration lane). The resulting traffic data provide fundamental information about the freeway merge behavior of ramp drivers. The merging position of the ramp vehicle was analyzed relative to the freeway lead

Table 1
The possible types of vehicle interactions

Row (i)	Column (j)	Freeway		Ramp	
		Col. 1 Lane 1	*Col. 2 Lane 2*	*Col. 3 Lane 1*	*Col. 4 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	None	Car following	Lane changing
	Lane 2	Merging	Almost none	Almost none	Car following

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. While building our model of the behavior of ramp drivers, we naturally took into consideration existing car-following models. 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 (Sarvi et al., 2002), we consider three stimuli affecting the ramp driver's 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 (1963) 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).

$$\begin{aligned} a_R(t+T) = {} & \alpha_0 + \alpha_1 \frac{V_R^m(t+T)}{[X_{Flead}(t) - X_R(t)]^{l_1}} \\ & \times [V_{Flead}(t) - V_R(t)] \\ & + \alpha_2 \frac{V_R^m(t+T)}{[X_R(t) - X_{Flag}(t)]^{l_2}} [V_R(t) - V_{Flag}(t)] \\ & + \alpha_3 \frac{1}{[X_{Flead}(t) - X_R(t)]^{l_3}} \{S(t) - f[v(t)]\} \end{aligned} \tag{1}$$

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 (meter)
$X_{Flead}(t)$ Location of the freeway lead vehicle at time t (meter)
$X_{Flag}(t)$ Location of the freeway lag vehicle at time t (meter)
$V_R(t)$ Velocity of the ramp vehicle at time 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 (meter)
$f[v(t)]$ Desired spacing as a function of speed (meter)
T Time lag or driver response time (seconds)
$\alpha_0, \alpha_1, \alpha_2, \alpha_3, m, l_1, l_2, l_3$ Parameters to be estimated.

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 of the MEX, which incorporated 200 samples were used to calibrate the hypothesized ramp vehicle acceleration–deceleration models. The results indicated that 90th percentile of ramp drivers respond to stimuli after a time gap of 0.7 seconds. Nonlinear and linear functional forms were used for the calibration of Equation (1) (estimated parameters for the linear model are $\alpha_0 = -0.134$, $\alpha_1 = 0.73$, $\alpha_2 = -0.51$, and for the nonlinear model are $\alpha_0 = 0.103$, $\alpha_1 = 1.84$, $\alpha_2 = -0.5$, $\alpha_3 = 0.134$). 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 $T = 0.7$ seconds 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 (1999). Therefore, we will use the linear acceleration–deceleration model shown in Equation (2) in the development of the FMCSP.

$$\begin{aligned} a_R(t+T) = {} & \alpha_0 + \alpha_1 [V_{Flead}(t) - V_R(t)] \\ & + \alpha_2 \frac{[V_R(t) - V_{Flag}(t)]}{[X_R(t) - X_{Flag}(t)]^b} \end{aligned} \tag{2}$$

where b is a known input parameter (Equation (2) is readily transformed to linear forms assuming $b = 2$ (Sarvi, 2000a)).

3 FMCSP: A MICRO SIMULATION MODEL

3.1 Outline of FMCSP

A periodic sampling method at intervals of 0.05 seconds is used for this micro-simulation model. The FMCSP simulation includes the merging section and the upstream/downstream sections (Sarvi et al., 2000b). These sections are treated as three distinct types, each with its own characteristics (see Figure 2).

The 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 allow time for the vehicles generated at the upstream ends of the ramp and freeway to form platoons while traveling through the 350-meter segment. At the beginning of the freeway segment, vehicles are dynamically generated based on the travel times of vehicles in the shoulder and median lanes of the freeway. The merging maneuver makes the travel time of vehicles in the freeway shoulder lane greater than that of vehicles in the median lane; hence, fewer vehicles are generated in the shoulder lane. The shorter travel time of the freeway median 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 are implemented in these segments in addition to the lane-changing maneuvers of vehicles moving from the freeway shoulder lane into the freeway median lane. The 10-meter segment between Zones 2 and 3 is defined as the terminal segment in which vehicles that have not yet merged are forced to merge. (3) Downstream segments (freeway lanes at Zone 3): In this 100-meter section after the merging section, free-flow traffic conditions are simulated. (4) Aggressive driver lane-changing model: This component models the lane-changing behavior of drivers who move from the freeway shoulder lane to the freeway median lane immediately before the merging section in order to avoid merging interactions. Direct observation and video data indicate that this lane-changing behavior reduces the flow rate of the freeway median lane and consequently affects the total output flow rate of the freeway. (5) Avoidance of the lane-changing model: This model implements the lane changing of vehicles from the freeway shoulder lane (within the merging section) into the freeway median lane. Often vehicles change lane, especially where the two ramp lanes merge, after their first merging to avoid the delay of a second merging.

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.

3.2 Calibration and validation process

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 (Figure 5). In the macroscopic analysis, the average speed, density, and volume computed using the FMCSP were compared with the values from real world traffic conditions (Figure 6).

To validate the simulation model, four traffic flows and two lane-changing maneuvers were compared with observation. The two lane-changing maneuvers considered were aggressive lane changing before the physical nose

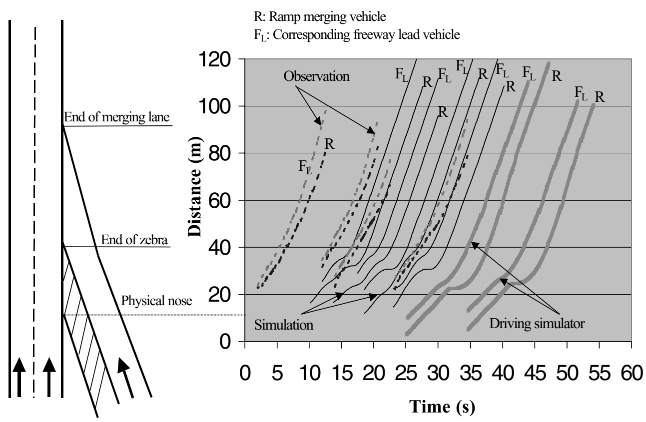


Fig. 5. Comparison of observed, simulation, and DS trajectories at Ichinohashi merging point (each pair of lines include ramp vehicle and its freeway leader vehicle).

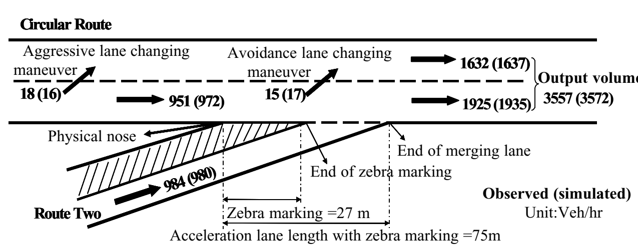


Fig. 6. Observed versus simulated traffic volumes (Ichinohashi merging point).

and avoidance lane changing within the merging section. As shown in Figure 6, good agreement was found between the real and simulated results for the traffic volumes of the freeway shoulder and median lanes after the merging section, the traffic volumes of the ramp lane and freeway median lane before the merging section, the number of lane-changing maneuvers before the physical nose, and the lane-changing maneuvers within the merging section.

Figure 5 shows a comparison between the simulated and observed trajectories of vehicles. Each pair of lines in this figure represents the ramp vehicle and its freeway lead vehicle. The slopes of the trajectory lines (speeds) for the simulated vehicles before and after the merging process are consistent with the observed slopes. The average speeds of the simulated ramp vehicle and its freeway leader vehicle during the course of merging maneuver (i.e., from the physical nose till the end of merging lane) are 5.24 m/s and 6.20 m/s, respectively, while the corresponding velocities observed for the real vehicles are 5.25 m/s and 6.24 m/s. Between the end of the zebra marking and the end of the merging lane, the average time (headway) between the ramp vehicle and its freeway leader is 1.8 seconds in the real situation and 1.95 seconds for the simulation. Additionally, a significant speed reduction immediately prior to the merging maneuver is observed in both the simulated and the real trajectories.

In addition to the trajectory analysis, the lane-changing maneuvers of vehicles in the FMCSP, as visualized using the graphic interface, were validated against real world video footage. This comparison considered the movement of the simulated vehicles prior to the merge end, and the merging maneuver of vehicles at the merging section. Furthermore, the effect of heavy vehicle percentage on maximum flow rate through the Ichinohashi merging section was studied via the FMCSP and compared with the data obtained from detector data taken over 2 months (Sarvi, 2000a). The results indicated that the FMCSP and detector data show an identical negative effect of heavy vehicles on maximum flow rate of the Ichinohashi section.

4 DRIVING SIMULATOR EXPERIMENTS

4.1 Integration approach

Having established that the FMCSP provides a good model of real merging conditions, the next step was to substitute one of the vehicles generated by the FMCSP with the DS. Using this approach, the FMCSP adjusts the speed of the surrounding vehicles (e.g., freeway lead and lag vehicles) in response to the incoming merging vehicle (i.e., DS driver) according to the car-following model, as explained above (see Figure 7). The FMCSP was extensively calibrated, improved, and modified to accurately simulate the actual traffic scenarios of the DS.

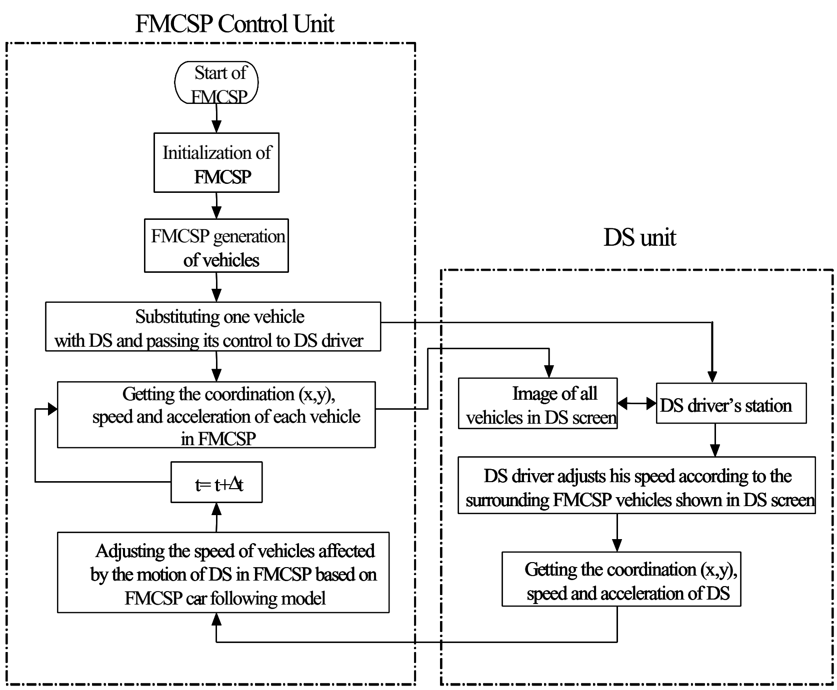


Fig. 7. Flowchart of DS and FMCSP integration.

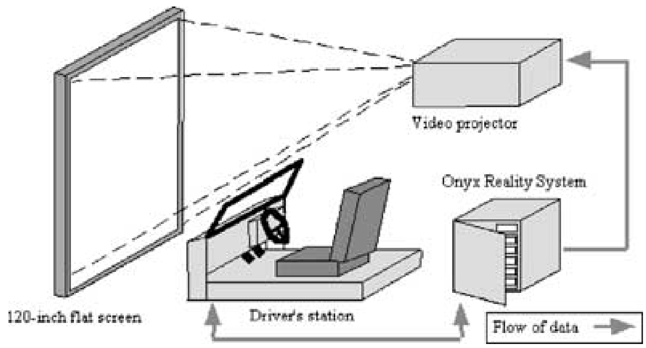


Fig. 8. Driving simulator configuration.

In addition, adjustments were made to the DS, which was originally designed for driving along straight freeway segments, to create a DS capable of simulating freeway ramp merging scenarios. Due to the sophisticated nature of this problem, a pilot study of the combined system of FMCSP and DS was conducted to investigate the feasibility of the approach and identify any deficiencies. Subsequently, the main experiment was carried out and the speed and position data were collected. Finally, two participants from the DS experiments drove an instrumented car through the real Ichinohashi merging section in order to gain a clearer perspective on the DS driver's behavior.

4.2 Outline of the driving simulator

The configuration of the driving simulator system used in this study is shown in Figure 8. The flow of data and test procedures implemented are described below.

Computer graphics of the virtual space were created by a workstation (Onyx Reality Station) and displayed on a flat 120-inch screen. The response of the subject to the image on the screen was monitored through the driver's station. Increase of accelerator or brake use was measured in 1% increments of acceleration or deceleration rates, respectively. The information measured through the driver's station was used to control the creation of the following computer graphics. The speedometer appearing in the driver's cab indicated the vehicle velocity. This velocity was calculated based on the rate at which the computer graphics were created, which was identical to the simulated vehicle dynamics. In the calculation of the vehicle velocity, the effects of air resistance, road surface resistance, and acceleration due to gravity (calculated according to the vertical alignment of the vehicle) were considered. The running noise of the vehicle was also an output. However, noise variations associated with the speed or roadside conditions were not reproduced. It is worth mentioning that the alignment of the driver's cab was rotated away from the vertical of the screen to provide DS drivers with a better field of view during merging (field of view visible by a slight turning of the head of DS driver is about 65 degrees). Figure 9 illustrates two graphical images of the DS (Ichinohashi merging point) as well as a photo of a DS driver driving in DS.

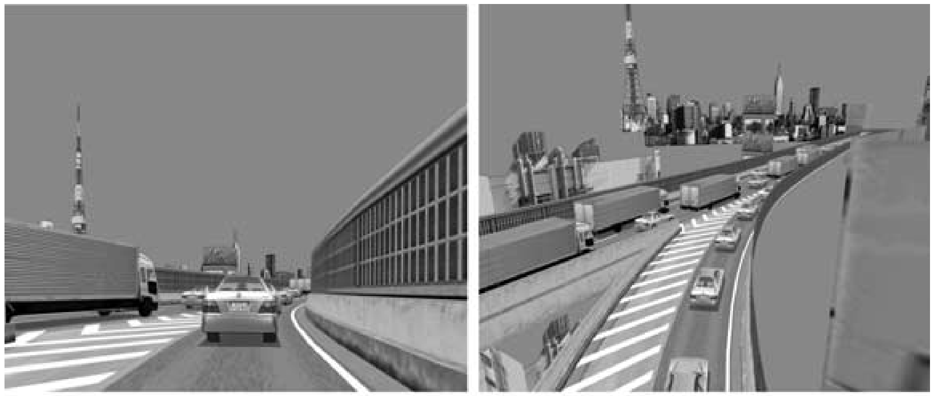
4.3 Data collection and experimental operation

One of the major tasks of this part of the research was the collection and reduction of experimental data describing DS operation. These data, which were used to compare the driving behavior of DS drivers and real world drivers, include freeway and ramp flow rate, freeway and ramp vehicle speed and acceleration–deceleration, vehicle type, freeway and ramp vehicle position in the network, and angle of ramp vehicle steering wheel.

The driving behavior data of 12 persons were collected while they were driving in the DS. The 12 drivers, who were selected from students and faculty staff, were all male and ranged from 20 to 46 years. Volunteers were not required to give information related to their driving history such as accident or traffic violations; the only requirement was a valid driving license. One might argue that the sample of 12 drivers used in this experiment may not be large enough to cover the variability in driving behavior. However, it is adequate to demonstrate the general trend of ramp drivers' driving behavior during freeway ramp merging maneuver. The procedure of the experiments and data collection of each participant is as follows:

1. To familiarize drivers with the operation of the DS, each participant drove the DS along an ordinary section of the designated highway at high speed for as long as they desired.
2. Each driver drove under the main scenario, which involved driving from the on-ramp and merging into the freeway stream under congested traffic conditions. The drivers started from the section almost 350 meters before the physical nose of the merging lane.
3. Finally, after sufficient practice each participant drove under the main scenario (merging from the on-ramp into the freeway stream) three times and the data were collected.

At the end of the experiments drivers completed a questionnaire that surveyed their views on the capability and reality of the DS. This information will be used to assist the design of future studies.



(a)

(b)

Fig. 9. (a) Driving simulator images. (b) A photograph of DS driver driving in DS.

4.4 Results and discussion

4.4.1 General behavior of driving simulator drivers. Drivers in the real world perform several tasks during the free-flow merging process. Michaels and Fazio (1989) define these tasks as follows: 1) tracking of the ramp curvature, 2) steering from the ramp curvature onto a tangent acceleration lane, 3) acceleration from the ramp controlling speed up to a speed closer to the freeway speed, 4) searching for an acceptance gap, and 5) steering from the acceleration lane onto the freeway lane or aborting. An important aspect of our DS study is to compare the performance and behavior of DS drivers with the characteristics of drivers in real merging situations. In addition, elucidation of the main characteristics of the ramp driver's behavior is important for evaluating the success of combining the DS and FMCSP to model freeway merging behavior. Because the behavior of merging ramp drivers is believed to be significantly influenced by the geometric configuration of the entrance ramp, as well as the location and behavior of the surrounding freeway and ramp vehicles (Sarvi et al., 2002), we carried out a DS study of the driving behavior at the Ichinohashi merging point. The results of this study were compared with observations from the real Ichinohashi merging point, and it showed the following general behavior of DS drivers during merging maneuvers on a congested freeway.

1. Driving Simulator drivers perform several tasks during the merging process under congested conditions: (a) tracking of the ramp curvature, (b) steering from the ramp curvature into an acceleration lane when the driver joins the tail of the queue that forms from the terminal section of the taper part of the merging section, (c) considering the spacing and relative speeds of the corresponding freeway lag and leader vehicles at the terminus of the merging section, and (d) steering from the acceleration lane into the freeway lane either by making a forced merge or accommodating the freeway lag vehicle.
2. Almost all drivers merge at the terminal part of the taper. In most cases, squeeze merging can be observed at the end of merging section. Gap searching and acceptance maneuvers do not take place.

3. In contrast to the real situation, where almost all merging drivers consider the freeway lag vehicle at the time of merging, DS drivers could not fully consider the lag vehicle because the DS is not equipped with back or side-view mirrors. Hence, the behavior of DS drivers is affected to a greater extent by the freeway lead vehicle than in the real situation.
4. No variation was observed among the three trials undertaken by each individual DS driver.

4.4.2 General behavior of ramp drivers in the acceleration lane. A ramp driver in the acceleration lane performs different tasks in a timesharing mode before merging onto the freeway stream, as described in the previous section. The way in which drivers perform these tasks varies from driver to driver. Below we give an overview of the fundamental phenomena that characterize DS merging operations.

The property of primary interest is the speed change profile of the DS vehicle as it travels along the acceleration lane and enters the freeway. These data indicate where and with what magnitude vehicles accelerate or decelerate, and give the speed at which vehicles enter the freeway in the merging area.

The speed data was measured at 0.05-second intervals during the DS experiments. Figure 10a shows samples of the time trajectory, speed, and acceleration profiles of two participants in this study. To gain an overall perspective of driver behavior, we averaged the speed profiles of 12 DS drivers. Figure 10b illustrates the average ramp vehicle speed profile measured from 20 meters prior to the physical nose. The curve illustrates that on an average ramp drivers decelerate on merging to adjust their speed to the speed of the freeway leader. Subsequently, drivers accelerate to join the freeway stream and then decelerate after entering the freeway stream to adjust their speed in response to the speed of their freeway leader. Finally drivers accelerate continuously and follow the leader ahead.

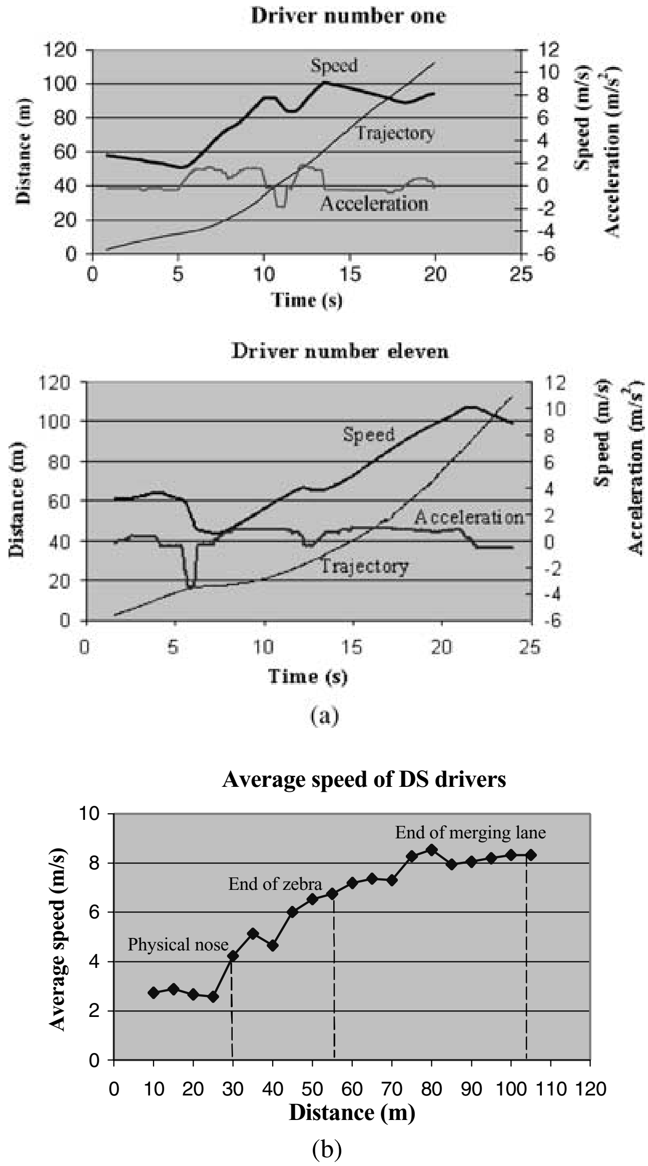


Fig. 10. (a) Speed profile of two participants of DS experiments. (b) Average speed profile of DS drivers.

4.4.3 Comparison of driving behavior of DS and an instrumented car. To gain a clearer understanding of the DS results, and to further compare DS and real world driving behavior, experiments were performed in which an instrumented car was driven through the merging point used for the DS experiments (the Ichinohashi merging section). Two drivers were used in these experiments, who were selected at random from the participants of the DS test (drivers 7 and 12). Each driver negotiated the merging point twice. Figures 11a, and b show the time trajectories and speed profiles of the DS and the instrumented car when driven by drivers 7 and 12, respectively. The over-reaction and sudden acceleration–deceleration amplitude evident in the DS results can be attributed to two factors. First, the braking and acceleration pedals of the DS are not sufficiently sensitive, and second, the perception of DS drivers is based only on the view of the surrounding traffic, whereas in the real world drivers also perceive changes in speed during acceleration–deceleration through gravitational acceleration. In addition, one should consider the merge timing adjustment when comparing the real and DS trajectories. Positions of corresponding lag vehicles of DS and real ramp vehicles are not the same. Taking into consideration the factors mentioned above, a dashed line can be drawn for each case as shown in Figures 11a and b, allowing comparison of the driving behavior of DS and

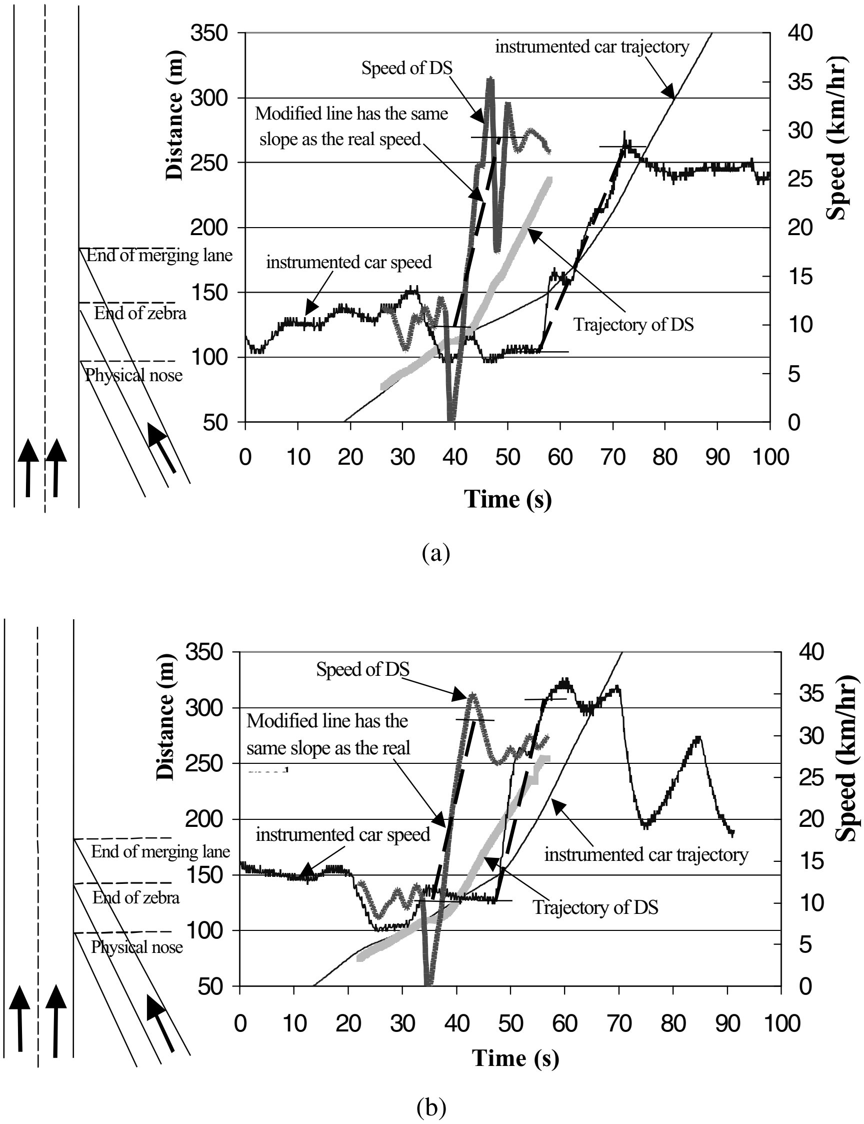


Fig. 11. (a) Comparison of DS and instrumented car driving behavior of driver 7 at Ichinohashi merging point. (b) Comparison of DS and instrumented car driving behavior of driver 12 at Ichinohashi merging point.

instrumented car drivers (i.e., the similarity of the slopes of the speed profiles). The similarity observed in the slopes of these lines indicates that the DS and real world drivers have similar acceleration–deceleration behavior. However, one might argue that the hard braking shown in the driving simulator results would be a disaster in the real world. An unprepared driver of the following car, who was not expecting the driver ahead to brake like that, would likely crash into the back end of the braking vehicle. Nonetheless, the main purpose of this research is to investigate the behavior of ramp platoon leader (i.e., DS driver). Consequently, the attitude of the ramp driver following the ramp platoon leader has no significant impact on this study. In addition, in order to avoid any collision to the back end of the DS a minimum safety space is always kept by FMCSP simulation program.

Finally, Figure 6 shows the observed time trajectories of merging vehicles at the Ichinohashi merging point (four different pairs of trajectories for a ramp vehicle and its freeway leader vehicle), the time trajectories from the FMSCP (four different pairs of trajectories for a ramp vehicle and its freeway leader vehicle), and the time trajectories from DS experiments (two different pairs of trajectories for a ramp vehicle and its freeway leader vehicle). The curves show similar slopes of the trajectories for the FMCSP, DS, and real situation, indicating similar general behavior of ramp drivers in all cases. In the real situation the average speeds of the ramp vehicle and its freeway leader vehicle during the course of merging maneuver, from the physical nose until the end of the merging lane, are 5.25 m/s and 6.24 m/s, respectively, while those of the DS trajectories are 5.18 m/s and 6.32 m/s, respectively. The time distance between the ramp vehicle and its corresponding leader vehicle is greater in the DS trajectories than in the simulated or observed trajectories. The observed average time distance between the ramp vehicle and its freeway leader vehicle, from the end of zebra marking till the end of merging lane, is 1.8 seconds in the real situation and 2.1 seconds in the DS results. As mentioned earlier, this difference can be partially attributed to insufficient sensitivity of the braking and acceleration pedals in the DS, as well as to inherent features of DS that are not completely analogous to the real world. Further investigation to overcome these deficiencies is warranted.

5 CONCLUSIONS AND RECOMMENDATIONS

This study describes the methodology for linking the FMCSP and a DS. This work was undertaken to compare the behavior of DS drivers (acceleration and deceleration behavior) with that of drivers in the real world as they carry out freeway ramp merging maneuvers under congested traffic conditions. To achieve this objective, the developed FMCSP was modified to simulate the actual traffic conditions for the DS. In addition, two participants of the DS experiment drove an instrumented car through the real Ichinohashi merging point. The results were compared with the DS results for the same drivers, giving us a clearer perspective on DS driver's behavior.

Using the DS, the general driving behavior of ramp drivers during merging maneuvers on a congested freeway was investigated and described. Comparison of the time trajectories of merging vehicles from the FMSCP simulations, DS experiments, and instrumented car study showed similar slopes of the trajectories (speeds) in the three sets of results, indicating similar general behavior of the ramp drivers. In addition, a significant speed reduction immediately prior to the merging maneuver into the freeway lane was observed in all trajectories. The results show that the FMCSP is capable of simulating the actual traffic conditions of the congested freeway ramp merging process, and that the insertion into a simulation of a vehicle controlled by a DS is a promising tool for the study of complicated ramp merging phenomena.

Although the results obtained from this study are encouraging, the limited number of drivers used in the comparison between DS and the real world makes the conclusions drawn from this study only tentative. However, the results presented here suggest the potential benefits of using a driving simulator as a data collection tool, and represent a new direction for the future investigation of ramp driver's merging behavior. Driving Simulator experiments offer many advantages over other methods such as a safe environment to study driver behavior in fine details as well as training drivers and therefore, deserve further evaluation using larger data sets.

Future studies could be improved by the use of a full vehicle cab or more advanced DS to create a more realistic driving atmosphere. In addition, the lack of rear and side-view mirrors in the DS is an important shortcoming that needs to be addressed. Our results show that ramp drivers use these mirrors when merging, especially in congested traffic conditions, and the lack of mirrors leads to an underestimation in the DS results of the effect of the freeway lag vehicle.

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