DEVELOPMENT OF A MICROSIMULATION PROGRAM TO STUDY FREEWAY RAMP MERGING PROCESS IN CONGESTED TRAFFIC CONDITIONS

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ABSTRACT

This work describes a micro simulation program that is developed to study freeway ramp merging phenomena under congested traffic conditions. First, the results of extensive macroscopic and microscopic studies are used to establish a model for the behaviour of merging drivers. A theoretical framework for modeling the ramp and freeway lag driver acceleration-deceleration behaviour is then presented. This methodology uses the stimuli-response psychophysical concept as a fundamental rule, and is formulated as a modified form of the conventional car-following models. Data collected at the two merging points of the Tokyo Metropolitan Expressway are used to calibrate the hypothesized ramp and freeway lag vehicle acceleration models. Next, based on this behavioural model, the Freeway Merging Capacity Simulation Program (FMCSP) is developed to simulate the actual traffic conditions. This model evaluates the capacity of a merging section for a given geometric design and flow condition. The validation of FMCSP performed at microscopic and macroscopic levels using the observed flow, vehicles trajectories, and lane changing maneuver. The developed FMCSP is applied to investigate the lane changing restriction strategy as well as the study of ramp driver behaviour by establishing a link to a driving simulator. The results indicated that the FMCSP is capable of simulating the actual traffic conditions of congested freeway ramp merging sections to study the complex ramp merging phenomena.

Key Words:
Micro simulation program, Freeway ramp merging, Driving behaviour, Congested traffic flow.

1. INTRODUCTION

Statistical analyses of observed volumes are usually employed in order to estimate the capacity of highway elements. Capacity of merging sections, however, is affected by many variables such as two directions of flow and variety of lane configurations, various geometric design and flow conditions. It is difficult to estimate the capacity of merging sections through statistical analysis based on observed capacity data for various geometry and flow conditions. Additionally, quite often, sufficient data can not be collected for the purpose of a particular study (e.g. lateral clearance impact on freeway merging capacity). Merging capacity still can not be estimated with sufficient accuracy, though extensive studies on merging sections have been performed mainly in the United States (Beaky 1938, Pinnell et al. 1960, Hess 1963, Wattlworth et al. 1967, Rottinghous 1974, Polus et al. 1985, 1987). Instead, this study focused on individual vehicular maneuvers to construct a simulation model for a merging section, since the merging capacity is possibly a consequence of the aggregation behaviour of each driver, and is not completely random but follows some fundamental disciplines. For this purpose, extensive microscopic data obtained from observation on two merging sections and a macroscopic study in several sections of the metropolitan expressway in Tokyo area is utilized and necessary data such as spacing and relative speeds of merging vehicles are obtained. A theoretical framework for modeling the ramp and freeway lag driver (approaching the ramp area from the freeway) acceleration-deceleration behaviour is presented. This methodology uses the stimuli-response psychophysical concept as a fundamental rule, and is formulated as a modified form of the conventional car-following models. Data collected at the two merging points are used to calibrate the hypothesized ramp and freeway lag vehicle acceleration models. Based on these analyses, a micro simulation model that intends to predict and evaluates the behaviour of drivers at merging sections under heavy traffic situation as well as to estimate the merging capacity is developed. The overall research approach is illustrated in Figure 1, emphasizing the fourth component, which represents this work.

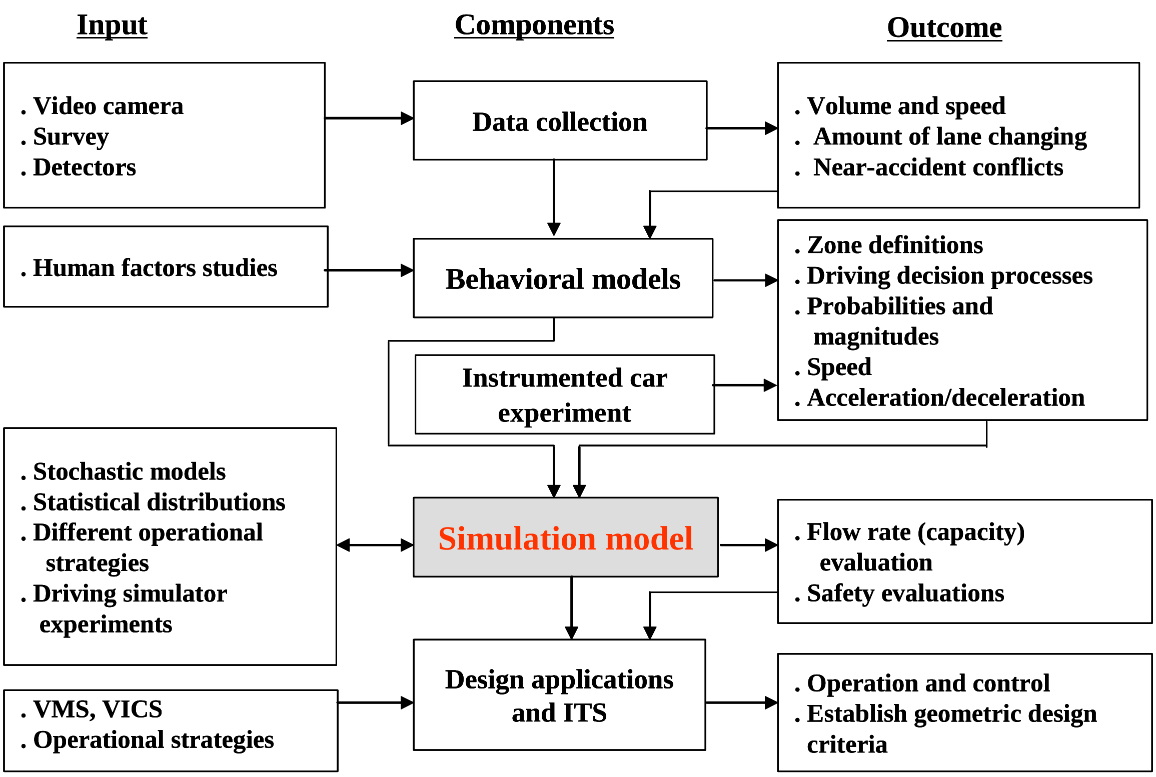


Figure 1 Conceptual flowchart for this study.

2. MODELING

2.1. Vehicle Interaction and Traffic Behaviour

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 2000, Sarvi et al. 2001). The decisions required in each zone can be expressed as follows.

Ramp Zone 1 (preliminary zone): A decision about how to arrive at Zone 2 (from lane one or two),

Ramp Zone 2 (merging zone): A decision about which two vehicles to merge between, Ramp Zone 3 (downstream zone): A decision about at what distance and speed to follow the vehicle in front,

Freeway Zone 1 (preliminary zone): Same as ramp Zone 1,

Freeway Zone 2 (merging zone): A decision as to which vehicle from the ramp should be permitted to merge,

Freeway Zone 3 (downstream zone): Same as ramp Zone 3.

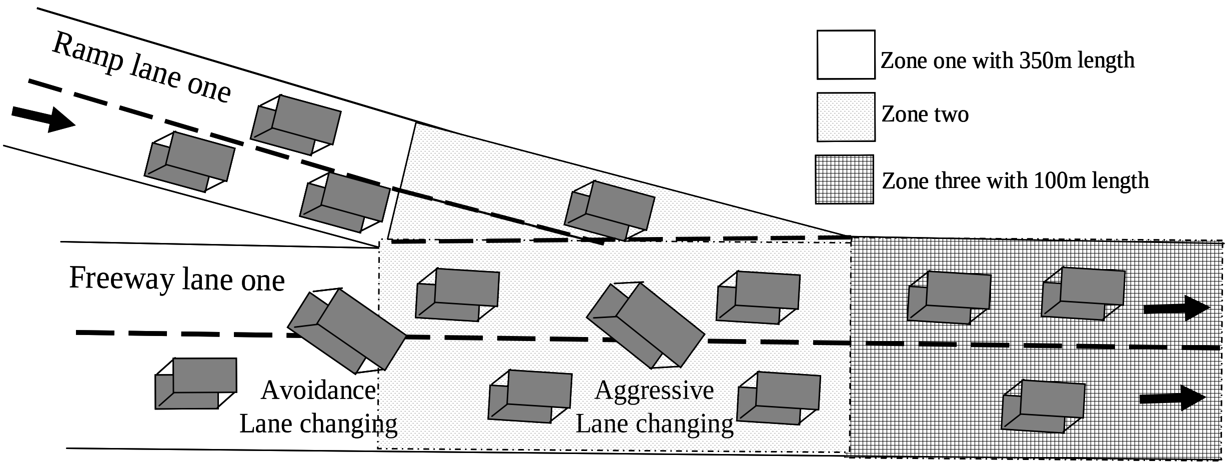
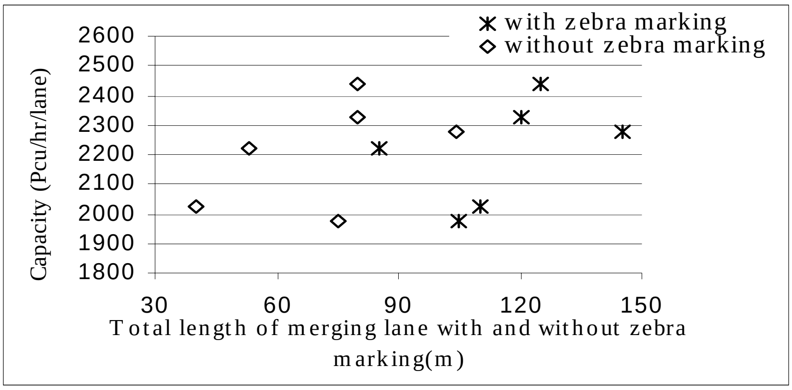


Figure 2 Zone specifications during freeway ramp merging maneuver.

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 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 et al 1991, Kita 1993, 1998, Ahmed et al. 1996, 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 thorough microscopic and macroscopic study and observations of the Tokyo Metropolitan Expressway (MEX) (Sarvi et al. 1999, 2001, 2002). These 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 (Sarvi et al. 2001). Therefore, in this study the gap searching and acceptance maneuver will not be addressed. The third driver decision, related to car-following behaviour, will be discussed later in this paper. Figures 4-a and 4-b demonstrate Hamazaki-bashi and Ichinohashi merging sections.



Figures 3 Relationship between total length of merging lane with and without zebra marking and merging capacity (15 minutes detector data extended to 1 hour).

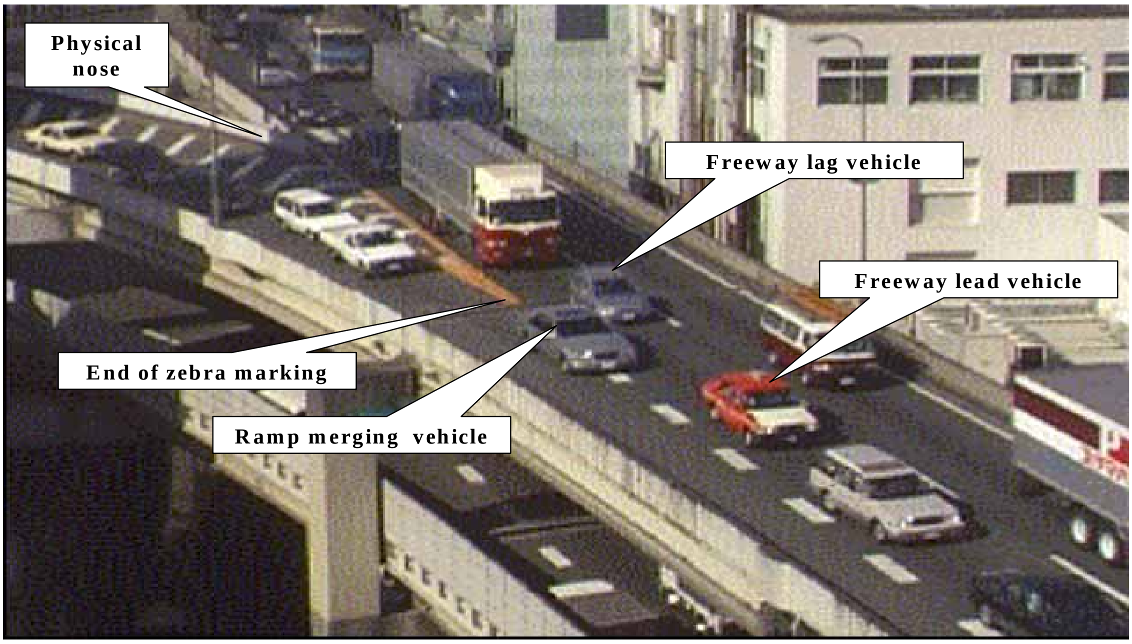


Figure 4-a Ichinohasi merging section.

Figure 4-b Hamazaki-bashi merging section.

2.1.2. Vehicle interactions and lane-changing behaviour

Table 1 lists the possible interactions between vehicles approaching and engaging the merging area under congested traffic conditions, as established by comprehensive observations (Sarvi 2000). 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 behaviour 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 behaviour has focused on gap acceptance behaviour and its applications. In this study, lane-changing behaviour in the merging area under congested traffic conditions was investigated at the microscopic and macroscopic (not individual vehicle) level (Sarvi et al. 2001, 2002). Two types of lane-changing behaviour are frequently observed in the merging sections. In Zone 1, aggressive drivers force their vehicles into the freeway/ramp lane 2 in order to avoid merging interactions. In Zone 2, some drivers force their vehicles into the freeway lane 2 in order to avoid the delay of a second merging. These lane-changing maneuvers affect 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 models both of these lane-changing maneuvers.

Table 1 The Possible Types of Vehicle Interactions.

Row (i) \ Column (j)		FREEWAY		RAMP	
		COL. 1	**COL. 2**	**COL. 3**	**COL. 4**
		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	None	Car following	Lane changing
	LANE 2	Merging	Almost none	Almost none	Car following

2.2. Methodologies for Modeling Ramp Driver Acceleration-Deceleration Behaviour

Freeway merge maneuvers are complex procedures involving various steps, for example a lane change, continuous acceleration, deceleration, and finally merging into a gap (Michaels and Fazio, 1989). 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 behaviour of ramp drivers. This investigation, which considered various types of entrance ramp, analyzed driver behaviour in terms of the speed of the ramp vehicle relative to its corresponding freeway lead and lag vehicles (see Figure 4-a), 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 behaviour during freeway merge maneuvers under congested traffic conditions. This microscopic analysis was performed separately for passenger cars and heavy vehicles.

The empirical investigation used video and image processing techniques to collect a wide range of microscopic 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 provides fundamental information about the freeway merge behaviour 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. When building our model of the behaviour 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 behaviour described by conventional car-following models. Essentially, the basis for modeling the acceleration-deceleration behaviour 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 microscopic analysis (Sarvi et al. 2002), we consider three stimuli affecting ramp driver behaviour: 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 behaviour 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)

$V_{Flead}(t)$: 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.

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 two hundred 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 0.66s.

Nonlinear and linear functional forms considering all possible combinations of the explanatory variable components of Eq. (1) were used for the calibration of proposed model (Sarvi 2000).

The best fitted nonlinear acceleration-deceleration model is:

$$a_R(t+T) = 0.103 + 1.84\frac{V_R^{0.0002}(t+T)}{[X_{Flead}(t) - X_R(t)]^1}[V_{Flead}(t) - V_R(t)] - 0.5\frac{V_R^{0.0002}(t+T)}{[X_R(t) - X_{Flag}(t)]^0}[V_R(t) - V_{Flag}(t)] + 0.134\frac{1}{[X_{Flead}(t) - X_R(t)]^0}\{S(t) - f[v(t)]\} \qquad (2)$$

with the R = 0.7 and T= 0.66sec.

The signs of the regression coefficients all have reasonable explanations. The positive sign of second term in Eq. (2) illustrates, assuming all other elements remain constant, that the ramp vehicle decelerate while approaching its freeway lead vehicle. The negative sign of the third term, conversely, indicates that if the speed of ramp vehicle is lower than its corresponding freeway lag vehicle, then the ramp vehicle accelerates in order to force a merging. Finally the positive sign of the fourth term indicates that the ramp driver always trying to maintain a desirable spacing based on its speed. The inclusion of the ramp vehicle current speed as one of the explanatory variables is necessary due to its significant regression coefficient.

2.3. Modeling Freeway Lag Driver Acceleration-Deceleration Behaviour

A modified form of the conventional car following models to accommodate the complex nature of a ramp vehicle acceleration-deceleration performance on acceleration lane is introduced in preceding section. The theoretical framework for modelling freeway lag vehicle (approaching the ramp area from the freeway) acceleration-deceleration behaviour is then built on the content of this work. In congested traffic situations, four stimuli are considered for evaluating the freeway lag vehicle driver response: relative speed regarding the freeway leader, relative speed regarding the ramp vehicle, spacing regarding the freeway leader, and the spacing regarding the ramp vehicle as it is reported by Sarvi et al. (2005a).

The hypothesized expression of freeway lag vehicle acceleration-deceleration behaviour is given as follows:

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

$$+ \alpha_2 \frac{V_{Flag}^{m}(t+T)}{[X_R(t) - X_{Flag}(t)]^{l_2}}[V_R(t) - V_{Flag}(t)]$$

$$+ \alpha_3 \frac{1}{[X_{Flead}(t) - X_{Flag}(t)]^{l_3}}\{S(t)_1 - f[v(t)]\}$$

$$+ \alpha_4 \frac{1}{[X_R(t) - X_{Flag}(t)]^{l_4}}\{S(t)_2 - f[v(t)]\} \qquad (3)$$

Where:

$a_{Flag}(t+T)$: Acceleration rate of the freeway lag 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)

$V_R(t)$: Speed of the ramp vehicle at time t (m/s)

$V_{Flead}(t)$: Speed of the freeway lead vehicle at time t (m/s)

$V_{Flag}(t)$: Speed of the freeway lag vehicle at time t (m/s)

$S(t)_1 = X_{Flead}(t) - X_{Flag}(t)$: Spacing between the freeway lag vehicle and the freeway leader vehicle at time t (m)

$S(t)_2 = X_R(t) - X_{Flag}(t)$: Spacing between the freeway lag vehicle and the ramp vehicle at time t (m)

$f[v(t)]$: Desired spacing as a function of speed (m)

T : Time lag or driver reaction time (s)

$\alpha_0, \alpha_1, \alpha_2, \alpha_3, \alpha_4, m, l_1, l_2, l_3, l_4$ are parameters to be estimated.

Eq. (3) has a nonlinear form. However, by assigning constant values to some of the parameters, Eq. (3) can be transformed to a linear form. A nonlinear and linear regression technique is performed in order to calibrate the parameters in Eq. (3) for different T values.

The calibration of the nonlinear acceleration-deceleration model in Eq. (3) is estimated using a nonlinear regression procedure considering all possible combinations of the explanatory variable components to find the best model.

The best fitted nonlinear acceleration-deceleration model is:

$$a_{Flag}(t+T) = -0.24 + 0.332\frac{V_{Flag}^{0.81}(t+T)}{[X_{Flead}(t) - X_{Flag}(t)]^{0.14}}[V_{Flead}(t) - V_{Flag}(t)]$$

$$+1.72\frac{V_{Flag}^{0.81}(t+T)}{[X_{R}(t) - X_{Flag}(t)]^{0.744}}[V_{R}(t) - V_{Flag}(t)]$$

$$+0.08\frac{1}{[X_{Flead}(t) - X_{Flag}(t)]}\{S(t)_1 - f[v(t)]\}$$

$$+0.16\frac{1}{[X_{R}(t) - X_{Flag}(t)]}\{S(t)_2 - f[v(t)]\} \qquad (4)$$

with the R = 0.73 and T= 0.66secm.

The signs of the regression coefficients all have reasonable explanations. The positive sign of second and third terms in Eq. (4) illustrates, assuming all other elements remain constant, that the freeway lag vehicle decelerate while approaching its leader vehicle (either freeway lead or ramp vehicle). The magnitude of the third term is bigger than the second term due to the higher interaction between the ramp and freeway lag vehicle compare to the one of the freeway lead vehicle (Sarvi et al. 2005a). Finally the positive sign of the fourth and fifth terms indicate that the freeway lag drivers always trying to maintain a desirable spacing based on their speed.

3. FMCSP: A MICRO SIMULATION MODEL

3.1. Outline of FMCSP

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. 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 m 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, separately for passenger and heavy vehicles, is implemented in these segments, utilizing the acceleration models described in the preceding sections, in addition to the lane-changing maneuvers of vehicles moving from the freeway shoulder lane into the freeway median lane. A 10-m segment between Zones 2 and 3 is defined as the terminal segment so that in which vehicles that have not yet merged are forced to merge. (3) Downstream segments (freeway lanes at Zone 3): In this 100-m section after the merging section, free-flow traffic conditions are simulated. (4) Aggressive driver lane-changing model: this component models the lane-changing behaviour 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 behaviour reduces the flow rate of the freeway median lane and consequently affects the total output flow rate of the freeway. (5) Avoidance 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 lanes ramp 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.

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

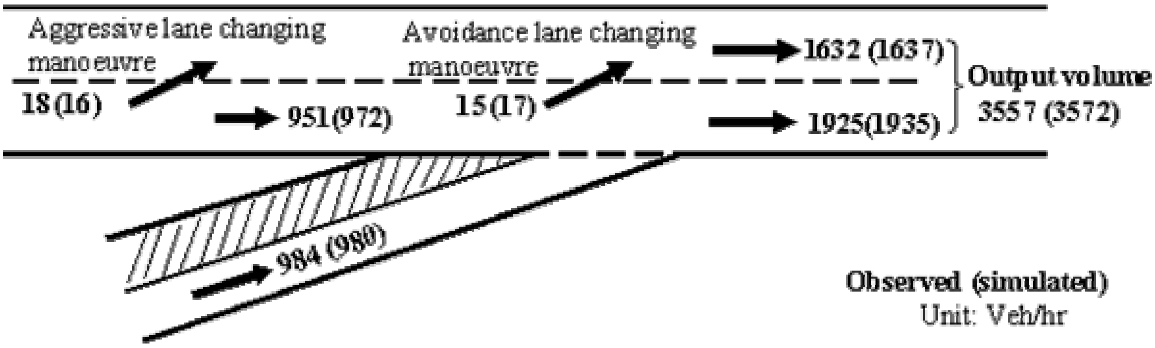


Figure 5 Observed versus simulated traffic volumes at Ichinohashi.

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 and avoidance lane changing within the merging section. As shown in Figure 5, 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 6 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 s in the real situation and 1.95 s for the simulation. Additionally, a significant speed reduction immediately prior to the merging maneuver is observed in both the simulated and the real trajectories.

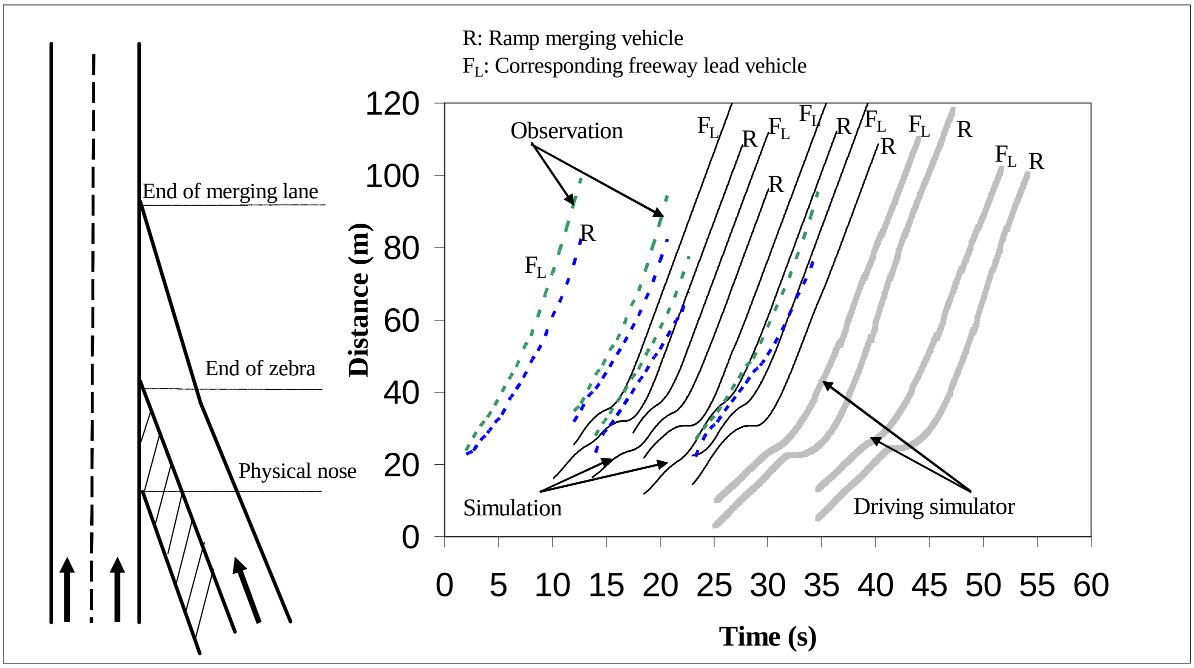


Figure 6 Comparison of observed, simulation, and DS trajectories at Ichinohashi

In addition to the trajectory analysis, the lane-changing maneuvers of vehicles in the FMCSP, as visualized using the graphic interface (see Figure 7), 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 impact of heavy vehicles percentage on maximum flow rate of Ichinohashi merging section was compared with the field data obtained from detector data taken over two months (Sarvi et al. 2005b). The results specified a good consistency between the FMCSP and detector data.

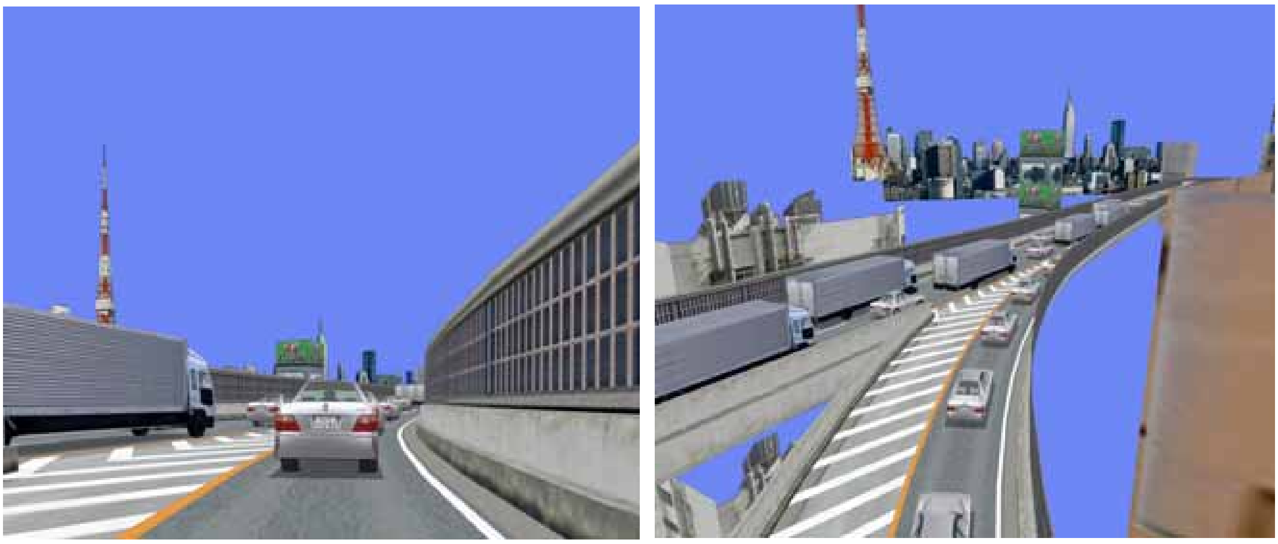


Figure 7 Two images of FMCSP

4. SIMULATION PROGRAM APPLICATIONS

A wide range of application options are available through the developed simulation program. Some initial results from a series of applications are presented in the following sections.

4.1. Developing control strategies for freeway merging points using FMCSP

Traffic congestion frequently occurs at merging bottleneck sections, especially during heavy traffic demand. Generally different empirical strategies could be applied at merging sections to increase the flow rate and decrease the accident rate. However, these strategies do not rely either on any behavioural characteristic of the merging traffic or on the geometric design of the merging segments. Therefore, the FMCSP is utilized to investigate different strategies during the merging process under congested situations in order to design safer and less congested merging points as well as to apply more efficient control at these bottleneck sections. Two groups of strategies were investigated and reported by Sarvi et al. (2003). The first group was related to the traffic characteristics, and the second group to the geometric characteristics. In the first group, the control strategies related to closure of freeway and ramp lanes as well as lane-changing maneuver restriction were investigated. The results and a brief discussion of implementation of a lane changing restriction are presented in the next section.

4.1.1. Lane Changing Restriction Strategy

Two types of lane changing frequently occurs at merging sections under congested traffic conditions as described in precede sections. The general objective of this section is to describe the impact of the lane-changing maneuver on the merging capacity, using the developed simulation program. FMCSP was employed to simulate the freeway merging process of the Ichinohashi merging point. The simulation results are shown in Tables 2-a to 2-c. Table 2-a shows the effect of aggressive lane changing on the maximum discharged flow rate of the merging section, while the avoidance lane changing is restricted. Conversely, Table 2-b shows the effect of avoidance lane changing on the maximum discharged flow rate of the merging section while the aggressive lane changing is restricted. The effect of combined aggressive and avoidance lane changing of vehicles on the maximum flow rate of the merging section is shown in Table 2-c. Additionally, Figure 8 depicts the general definition of items used in Tables 2-a to 2-c. Results indicate that by either increasing the aggressive or avoidance lane-changing maneuvers, the maximum discharged flow rate of the merging section continuously decreased. The percentage of aggressive and avoidance lane changing presented in tables 2-a to 2-c are in agreement with the observed percentage.

TABLE 2-a Aggressive Lane Changing Maneuver Analysis at Ichinohashi (simulation result)

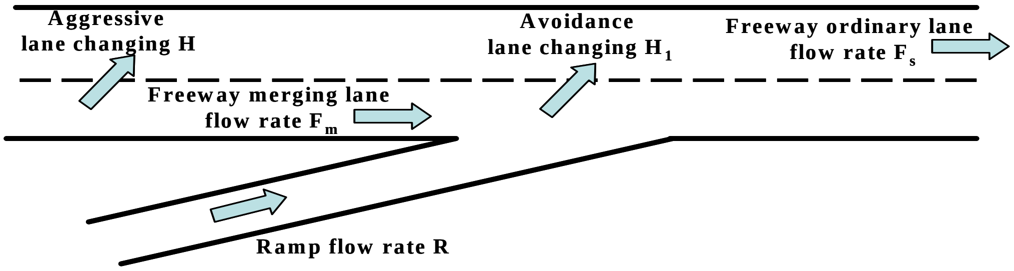
	Ramp	**Freeway**			
Lane changing percentage	**R** Ramp flow rate (veh/hr)	**Fm** Merging lane flow rate (veh/hr)	**Fs** Ordinary lane flow rate	**Fm+R+Fs-H1** Total discharge flow rate (veh/hr/2-lane)	Capacity change (percentage)
0	975	970	1622	3567	
1.8	972	970	1607	3550	-0.49
3.5	970	970	1606	3547	-0.56
5.1	968	967	1582	3517	-1.42
7.2	963	962	1565	3490	-2.22

TABLE 2-b Avoidance Lane Changing Maneuver Analysis at Ichinohashi (simulation result)

	Ramp	Freeway			
Lane changing percentage	**R** Ramp flow rate (veh/hr)	**Fm** Merging lane flow rate (veh/hr)	**Fs** Ordinary lane flow rate	**Fm+R+Fs-H1** Total discharge flow rate (veh/hr/2-lane)	Capacity change (percentage)
0	975	970	1622	3567	
5	1002	1025	1630	3498	-1.9
7	1015	1029	1635	3482	-2.32
14.3	1047	1038	1645	3432	-3.78

TABLE 2-c Total Lane Changing Maneuver Analysis at Ichinohashi (simulation result)

	Ramp	Freeway			
Lane changing percentage	**R** Ramp flow rate (veh/hr)	**Fm** Merging lane flow rate (veh/hr)	**Fs** Ordinary lane flow rate	**Fm+R+Fs-H1** Total discharge flow rate (veh/hr/2-lane)	Capacity change (percentage)
0	975	970	1622	3567	
2	985	977	1635	3562	-0.14
2.5	985	980	1635	3560	-0.21
3.6	993	987	1630	3547	-0.6
4	985	982	1632	3540	-0.77
6.4	1002	998	1635	3530	-1.05
7.9	995	985	1617	3495	-2



$$\text{Aggressive lane changing percentage} = \frac{H}{(H + F_m)}$$

$$\text{Avoidance lane changing percentage} = \frac{H_1}{(F_m + R)}$$

$$\text{Total lane changing percentage} = \frac{H + H_1}{(F_m + R + F_s - H_1)}$$

Figure 8 Lane changing definition used in Tables 2-a to 2-c.

4.2 Study of freeway ramp merging process using FMCSP and a driving Simulator

Carmakers, suppliers and transport research laboratories commonly employ driving simulators in research and the 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 research (Upchurch et al. 2002, Knodler et al. 2005, Essam et al. 2005). One of the first attempts to utilize a driving simulator to study freeway ramp merging phenomena was introduced and presented by Sarvi et al. (2004). The following section briefly describes the methodology for linking a driving simulator (DS) into the FMCSP in order to compare the behaviour of DS drivers with that of drivers in the real world as they carry out freeway ramp merging maneuvers.

4.2.1. Comparison of driving behaviour in DS with the one in the real world

The DS and simulation were combined by replacing one vehicle in the FMCSP by 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 models, as explained earlier. The FMCSP was extensively calibrated, improved, and modified to accurately simulate the actual traffic scenarios of the DS. The driving behaviour data of 12 people were collected while they were driving in the DS (see Figure 9). In addition, two participants of the DS experiments drove a sophisticated instrumented car through the real Ichinohashi merging section. The driving behaviour data from the DS, instrumented car, and observation of drivers were compared to investigate the behaviour of DS driver and examine differences between the behaviour of drivers using simulators and that in the real world (see Figure 6). The results indicated that the FMCSP is capable of simulating the actual traffic conditions of 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.

Figure 9 A photograph of DS driver driving in DS.

5. CONCLUSION

Traffic surveys, macroscopic and microscopic studies are performed at several merging sections on the Tokyo Metropolitan Expressway and a particular method to deal with these observed data is established. A theoretical framework for modeling the ramp and freeway lag driver acceleration-deceleration behaviour is presented. This methodology uses the stimuli-response psychophysical concept as a fundamental rule, and is formulated as a modified form of the conventional car-following models. Data collected at the two merging points of the Tokyo Metropolitan Expressway are used to calibrate the hypothesized ramp and freeway lag vehicle acceleration models. Furthermore, the lane changing maneuver of freeway aggressive vehicles before merging end as well as avoidance lanes changing are presented and taken into consideration.

Based on the behavioural model as an evaluation tool, a multi-purpose micro simulation program, FMCSP, has been developed. The validation of FMCSP performed at microscopic and macroscopic levels using the observation flow and lane changing maneuver at the Hamazaki-bashi and Ichinohashi interchanges under congested traffic situation. It is found that simulated value of discharged volumes and lane changing maneuver as well as the observed and the simulated trajectories of vehicles fitted well with that observed. It is also found that the impact of heavy vehicle percentage on the merging capacity of FMCSP is in agreement with the observed data. Finally the developed simulation program is applied successfully to investigate variety of freeway and ramp merging strategies as well as to establish a link with a driving simulator to study ramp driver's behaviour. Future improvements such as incorporation of the effects of vertical alignment, lane width, and lateral clearance needed to improve the functionality of FMCSP.

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