MACROSCOPIC STUDY OF FREEWAY RAMP MERGING PHENOMENA OBSERVED IN TRAFFIC CONGESTION

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Abstract: In Tokyo Metropolitan Expressway, 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 neither on any behavioral characteristic of the merging traffic nor on the geometric design of the merging segments. Therefore, a three years extensive study has been undertaken to investigate traffic behavior and characteristics during the merging process under congested situation to design a safer and less congested merging points and more efficient control at these bottleneck sections. The overall research approach is illustrated in Figure 1, emphasizing the first component, which represents this work. That is, this work focuses on macroscopic study of traffic behavior and characteristic during merging maneuver.

Key words: Freeway ramp merging, Macroscopic study, Congested traffic situation

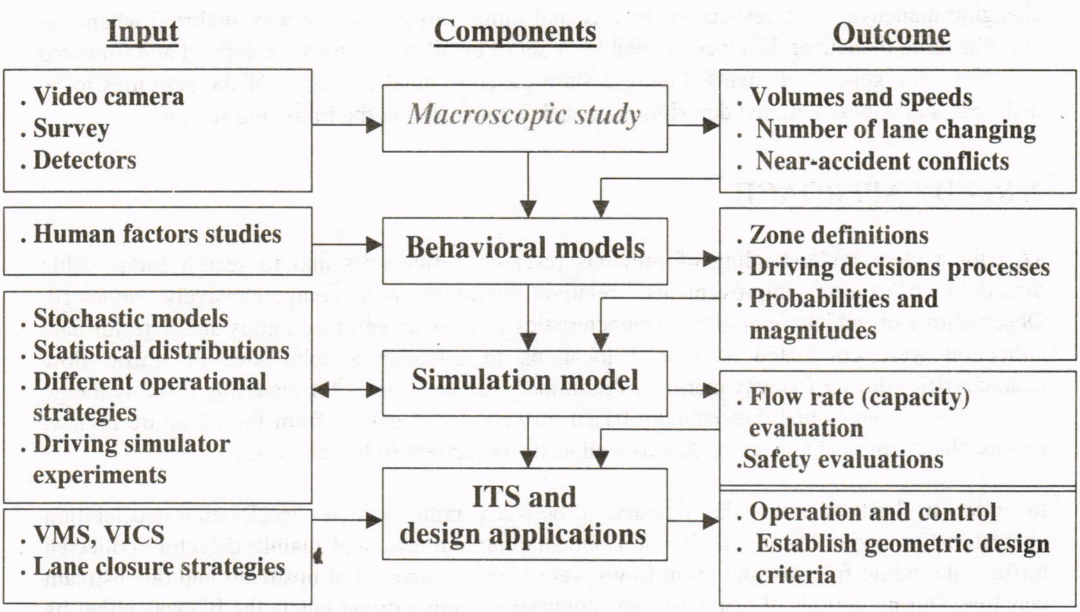

Figure 1. Overall research flowchart with emphasize on this work component

1. INTRODUCTION

At merging sections, traffic jams frequently occur especially under the heavy traffic demand. Because of the drop in the lane of merging sections, vehicles on merging lane compete for space. These sections may have no problem if their lengths and number of lanes or in other word their geometric design is sufficient. However, such merging sections are possibly bottlenecks when merging sections with sufficient length and good geometric design are difficult to construct, as is often the case with construction in urban areas, due to restricted budget etc.

On the other hand, a relationship between geometric and traffic characteristic of merging sections and capacity is not clearly known yet. Furthermore, macroscopic aspects of traffic behavior like lane changing maneuver before and within a merging section influence not only the ramp-freeway junction but also the upstream/downstream freeway lanes. Unfortunately, there have been relatively few publications devoted to the study of traffic behavior and characteristic in the merging section under congested situation. Therefore, it becomes important to evaluate capacities of merging sections in relation to their geometry and traffic characteristics. In order to estimate the capacity of normal sections (Basic freeway segments), statistical analyses based on observed volume for various conditions are usually employed. For estimating the capacity of merging sections, macroscopic and microscopic methods can be used, however, the macroscopic approach is very useful tool for validating the microscopic simulation methods. The main objective of this study is to investigate traffic behavior and characteristic during merging under congested situation when the demand exceeds capacity.

Traffic data capturing a wide range of traffic and geometric information were collected using detectors, videotaping, and surveys at several interchanges in Tokyo Metropolitan Expressway (MEX). Maximum discharged flow rate of the head of the queue (Bottleneck capacity) at merging sections in conjunction with traffic and geometric characteristic was analyzed. Lane changing maneuver with respect to freeway and ramp traffic behavior was analyzed where the lane changing maneuver data were available. A set of detailed activities are defined and followed to achieve the general elements. Figure 2 shows a conceptual flowchart of the activities to be included, and a more detailed description of each is presented in the following section.

2. STUDY APPROACH

To gain a clear understanding of previous research deficiencies and to search for possible directions of future improvements, relative literature was comprehensively reviewed. Observations of vehicle operational characteristics in freeway entrance ramps and detector data collection were conducted at several locations to establish a solid idea of traffic flow characteristics during freeway merging. Preliminary methodologies for modeling freeway merge behavior were developed conceptually based on knowledge gained from the literature review, on-site observation, and detector data as well as the objectives to be achieved.

In order to best describe the interaction between ramp vehicle acceleration-deceleration characteristics under congested situation, videotaping, surveys, and mainly detectors collected traffic data, while freeway and ramp flows were highly congested at upstream and downstream was free. During periods of heavy freeway congestion a ramp driver enters the freeway either by forcing a merge or by the accommodation of freeway lag vehicle. To develop a macroscopic freeway merge behavioral model as well as capacity evaluation with respect to the traffic and geometric characteristics, the collected field data such as freeway and ramp flow rate, freeway

and ramp vehicle speeds, occupancy, and lane changing behavior were used to identify and quantify key variables. Detailed data collection technique is described in the next section.
The data were applied to establish macroscopic driver behavior concepts such as lane changing (see section 4.3 for the macroscopic lane changing explanation), zone definition, and driver decision process. In addition, an extensive capacity estimation and evaluation analysis and its relation to the geometric and traffic characteristics at merging points have been performed. The final models expected in this research are the most appropriate methodologies for modeling ramp vehicle behavior during merging based on the available data.

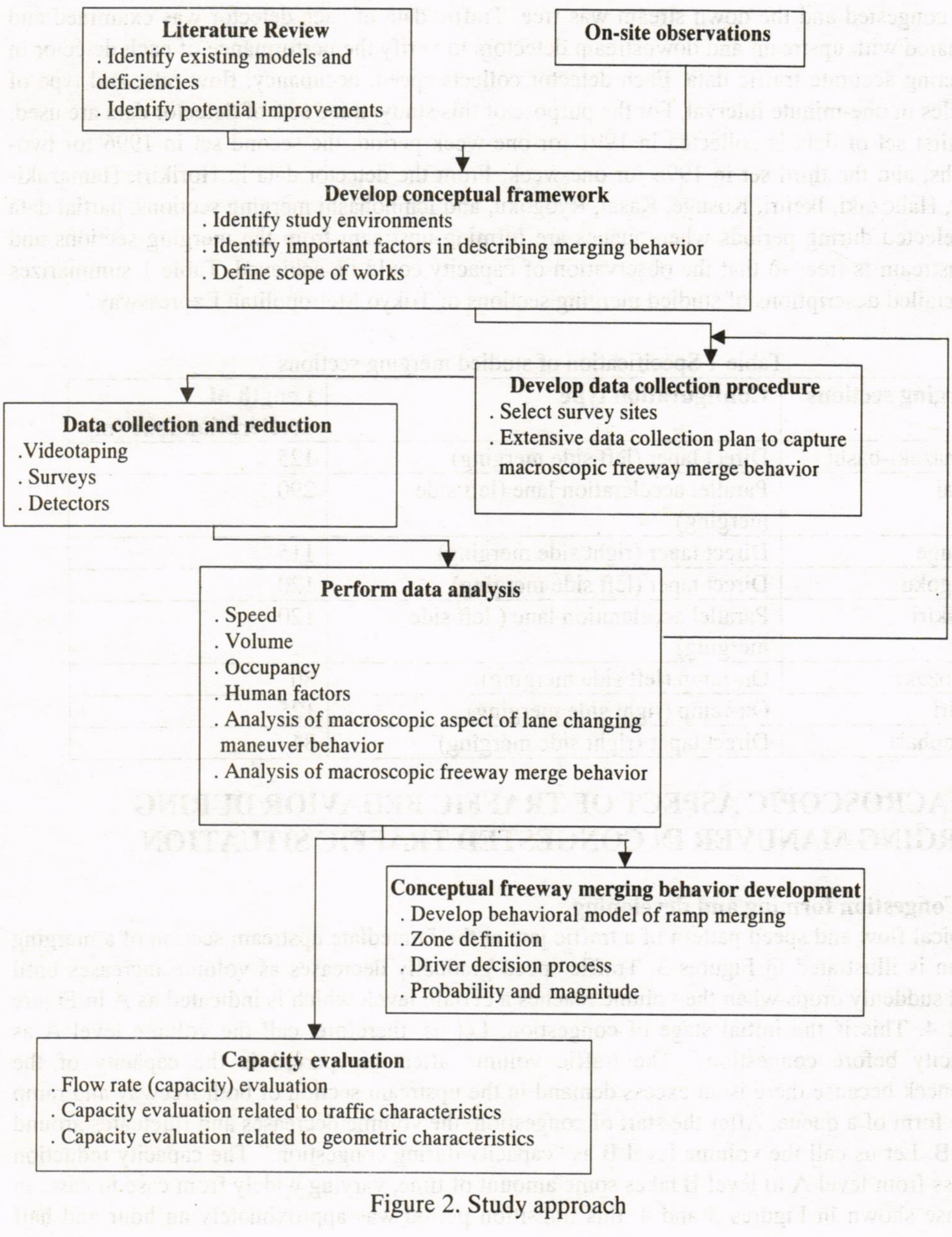

Figure 2. Study approach

3. DATA COLLECTION

One of the major tasks of this part of research is the collection and reduction of field data to be used in freeway ramp merging behavior model study. This data include freeway and ramp flow rate, freeway and ramp vehicle speeds, occupancy, and lane changing behavior, steering maneuver, and any other data necessary to define and model the macroscopic aspect of merging process as well as capacity estimation and evaluation. In this research, detectors mainly collected traffic data. In addition to detector data, surveys also were performed at Hamazaki-bashi and Ichinohashi interchanges as well as Ikejiri on-ramp of urban expressways in Tokyo area. Traffic data were collected during congested traffic situation while the upstream of ramp and freeway were congested and the down stream was free. Traffic data of each detector was examined and compared with upstream and downstream detectors to verify the performance of each detector in collecting accurate traffic data. Each detector collects speed, occupancy, flow rate, and type of vehicles in one-minute interval. For the purpose of this study, three sets of detector data are used. The first set of data is collected in 1991 for one-week period, the second set in 1996 for two-months, and the third set in 1998 for one-week. From the detector data in Horikiri, Hamazaki-bashi, Hakozaki, Ikejiri, Kosuge, Kasai, Ryogoku, and Ichinohashi merging sections, partial data are selected during periods when queues are forming upstream from the merging sections and downstream is free, so that the observation of capacity could be achieved. Table 1 summarizes the detailed descriptions of studied merging sections of Tokyo Metropolitan Expressway.

Table 1 Specification of studied merging sections

Merging sections	Configuration type	Length of acceleration lane (m)
Hamazaki-bashi	Direct taper (left side merging)	125
Kasai	Parallel acceleration lane (left side merging)	290
Kosuge	Direct taper (right side merging)	115
Ryogoku	Direct taper (left side merging)	120
Horikiri	Parallel acceleration lane (left side merging)	120
Hakozaki	On-ramp (left side merging)	80
Ikejiri	On-ramp (right side merging)	125
Ichinohasi	Direct taper (right side merging)	84

4. MACROSCOPIC ASPECT OF TRAFFIC BEHAVIOR DURING MERGING MANUVER IN CONGESTED TRAFFIC SITUATION

4.1. Congestion forming and developing

A typical flow and speed pattern of a traffic jam at the immediate upstream section of a merging section is illustrated in Figures 3. Traffic speed gradually decreases as volume increases until speed suddenly drops when the volume reaches a certain level, which is indicated as A in Figure 3 and 4. This is the initial stage of congestion. Let us, therefore, call the volume level A as "capacity before congestion." The traffic volume after this period is the capacity of the bottleneck because there is an excess demand in the upstream section of both freeway and ramp in the form of a queue. After the start of congestion, the volume decreases and fluctuates around level B. Let us call the volume level B as "capacity during congestion." The capacity reduction process from level A to level B takes some amount of time, varying widely from case to case. In the case shown in Figures 3 and 4, this transition period was approximately an hour and half between 7.30 a.m. to 9 a.m. and one hour between 9 a.m. to 10 a.m. respectively. The capacity during congestion fluctuates around level B and again may increase toward the end of congestion. A number of similar results have been obtained at the major bottleneck on Tokyo Metropolitan Expressway, as shown in Table 2. It has been shown that capacities during congestion differ from one bottleneck to another and range between 2163 and 1651 veh/hr/lane.

Table 2 Geometric and flow conditions of major bottleneck merging

Merging Sections	Configuration type	Capacity (Veh/hr/lane)	Capacity (Pcu/hr/lane)
Hamazakibashi	Direct Taper	Old=2071,New=1944 Long period=1968	Old=2298,New=2299
Kasai	Parallel acceleration lane	Old=1858,New=2067	Old=2123,New=2458
Kosuge	Direct Taper	Old=1824,New=2021	Old=2079,New=2204
Ryogoku	Direct Taper	Old=1871,New=1847	Old=1922,New=1973
Horikiri	Parallel acceleration lane	New=2068	New=2255
Ichinohashi	Direct Taper	New=1764	New=1896
Hakozaki	On Ramp	Old=2163,New=2051	Old=2281,New=2174
Ikejiri	On Ramp	Old=1846,New=1679 Long period=1651	Old=1990,New=1889

Passenger Car Equilivalient=1.5 Pcu/heavy vehicle
The old data is based on May 1991. The New data is based on May 1998
The long period data is based on May 1995

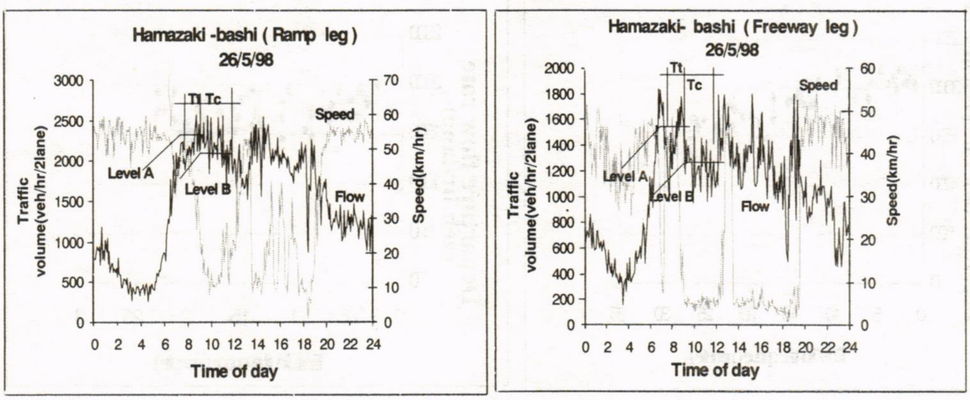

Figure 3. Typical example of metropolitan merging section congestion (5 min data of detectors at upstream of the merging section extended to 1 hour).

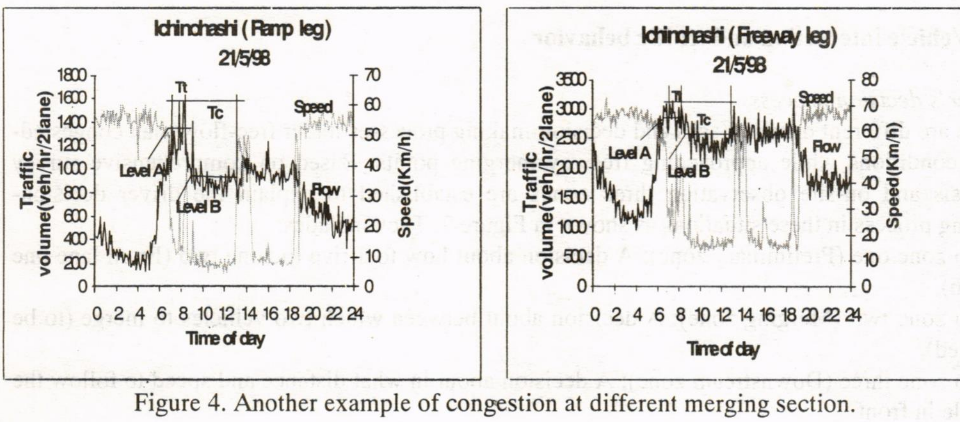

Figure 4. Another example of congestion at different merging section.

4.2. Transition from free flow to congested flow

The time period of Tt in Figure 3, during which the flow rate drops from level A to level B, is transition period from free flow to congested flow. The drivers seem to switch their car-following behavior from the free flow manner to congested flow manner during the time period Tt. The transition period Tt varies widely as illustrated by Figures 3 and 4. Figures 5 and 6 demonstrate the plots of the departure flow rates during Tt and Tc (From the beginning until end of congestion) of the cases in Figures 3 and 4 against duration of the average time that the drivers have spent in the queue. Based on Figure 5, there are two groups of plots that corresponded to the transition period and the steady congestion period. The transition of the driver behavior from free flow to congested flow is completed around 15 minutes (In the case of Ryogoku it is around 7 minutes). Therefore based on Figure 5, it can be concluded that drivers start switching their behavior of car-following from free flow mode to congested flow mode when they are caught in the queue, and complete the switching when their time in the queue reaches around 15 minutes (Comprehensive car-following study has been carried out, however for the sake of brevity the results are not present here. The summarized results can be found in reference 15). Figure 5, further illustrates the reduced departure flow rates during congestion as the time in queue increased. Drivers seem to gradually change their pattern of car-following becoming less sensitive and cautious as they are caught in the queue for longer periods.

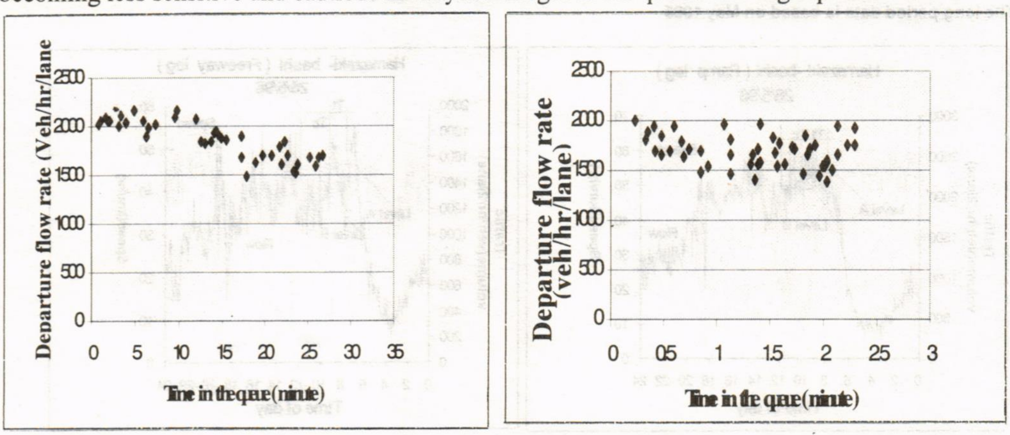

Figure 5 and 6 Departure flow rate vs. time in the queue for the congestion case shown in Figure 3, Ichinohashi, and 4, Hamazki-bashi (5 minutes moving average at 5 minute intervals).

4.3. Vehicle interaction and traffic behavior

Driver's decision process

There are different drivers' tasks and decision-making processes under free-flow than congested-flow conditions while approaching freeway merging points. Based on comprehensive survey analysis and on-site observation three zones are established to explain the driver decision-making process in these situations as shown in Figure 7. 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 the 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 (MEX) it was found that drivers mostly merge one by one at the terminus part of the merging section (more than 94%) (16). The third driver decision is related to the known car-following behavior and will not be dealt in this paper.

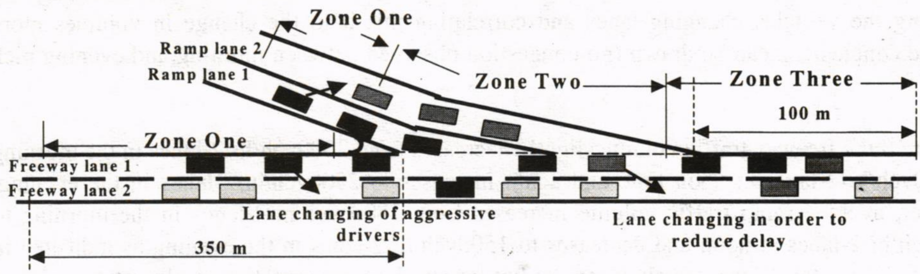

Figure 7. Definition of the three zones and lane changing phenomena.

Drivers interactions and lane changing behavior

The possible traffic interaction between vehicles approaching and engaging the merging area under congested traffic condition is described in Table 3. It is based on comprehensive observations. Table 3 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.

Table 3: Possible interactions of traffic flows in the merging area

i \ j		**Freeway**		**Ramp**	
		Lane one	*Lane two*	*Lane one*	*Lane two*
Freeway	*Lane one*	**Car Following**	**Lane Changing**	**Slow down to Provide right-of-way**	**Slow down to Provide right-of-way**
	Lane two	**None**	**Car Following**	**None**	**None**
Ramp	*Lane one*	**Merging**	**None**	**Car Following**	**Lane Changing**
	Lane two	**Merging**	**Almost None**	**Almost None**	**Car Following**

For years lane changing behavior process has been a very interesting and much discussed topic. Research on several elements of drivers during lane changing behavior has been performed, however, main focus has been on gap acceptance/rejection behavior and its application. In other words, many models have been introduced in order to explain lane-changing phenomena but mainly concentrating on the microscopic aspect. In this study, lane-changing behavior in the merging area under congested situation has been studied at the macroscopic (Not individual vehicle) level of the MEX and is described in a following section. 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 affect 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. In Figure 8 through 13 the lane changing behavior of the Hamazaki-bashi merging section of MEX (Based on two-month detector data) can be seen. That is the collection of data includes video analyses of both the traffic volumes and the number of lane changing. By observing the vehicles changing lanes and correlating this it to the change in volumes more concrete conclusions can be drawn (no congestion observed between morning and evening pick hours).

In Figure 8 the freeway traffic volume slightly decreases from 2000veh/hr/2-lanes in the morning to 1900veh/hr/2-lanes at noon time and again increases to 2500veh/hr/2-lanes in the evening. However, average ramp traffic volume increases from 1800 veh/hr/2-lanes in the morning to 1900 veh/hr/2-lanes at noon and decreases to 1500veh/hr/2-lanes in the evening as indicated in Figure 8. The total discharged flow rate of bottleneck during congestion is almost constant at 4000veh/hr/2-lanes. There is some kind of competition between the ramp and freeway drivers for space and consequently the discharged flow rate is almost constant at 4000veh/hr/2-lanes. In the evening, the ramp drivers may be more hesitant to merge (Perhaps due to insufficient lighting). Therefore, the freeway drivers move faster and the flow increases to 2500veh/hr/2-lanes.

The total number of lane changing in the freeway, which includes lane changing in zones one and two, is shown in Figure 9. The average volume of freeway lane two (Non-merging) increases with time from 1450 to 1700 veh/hr/lane and simultaneously the average volume of freeway lane one (Merging lane) increases from 520 to 800 veh/hr/lane. At the same time, the average total number of lane changing decreases from 650 to 500 veh/hr. In other words, by increasing the traffic volume of freeway lane two, the chances for lane changing of freeway lane one decrease, consequently the traffic volume of freeway lane one increases resulting in total lane-changing reduction.

The interaction between freeway lane one and ramp lane one is shown in Figure 10. By increasing the average volume of freeway lane one from 520 to 800 veh/hr/lane with time, the average volume of ramp lane one decreases from 750 to 550 veh/hr/lane, and as a result the total average volume of ramp lane one plus freeway lane one slightly increases from 1400 to 1500 veh/hr. These findings suggest that while the volume of freeway lane one increases due to reduction of lane changing as a consequence the volume of ramp lane one decreases.

The interaction between freeway lane one and ramp lane two is shown in Figure 11. When the average volume of freeway lane one increases with time from 520 to 800 veh/hr/lane, the average volume of ramp lane two slightly decreases from 1050 to 950 veh/hr/lane. This indicates that the effect of flow rate of freeway lane one on flow rate of ramp lane two is less than that on the flow rate of ramp lane one. The discharged volumes of freeway lane one and two as well as the ramp lane during congested traffic situations are shown in Figure 12 and 13, respectively. Particularly in the morning, the average volume of freeway lane one is one third of volume of freeway lane two. For the ramp, the average volume of ramp lane one especially in the evening is half of the volume of ramp lane two. These results led us to propose the strategy of lane one closure of both the freeway and the ramp in order to maximize the flow and minimize conflicts between vehicles.

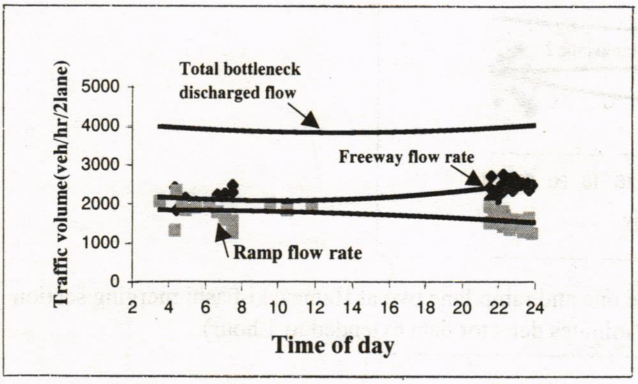

Figure 8. Total discharged flow rate, ramp flow rate, and freeway flow rate at Hamazaki-bashi merging section vs. time of day (15 minutes detector data extended to 1 hour).

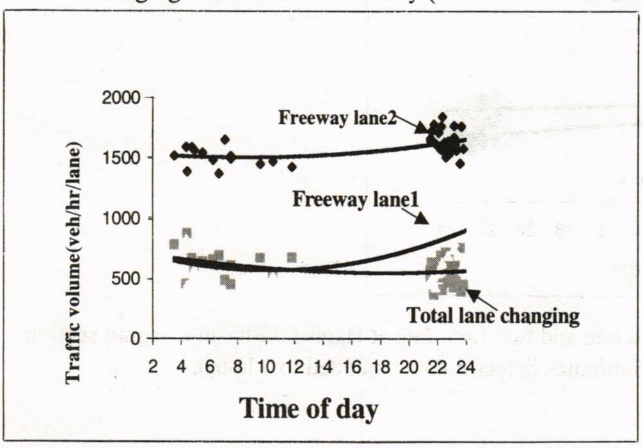

Figure 9. Freeway lane two flow rate, freeway lane one flow rate, and total lane changing at Hamazaki-bashi merging section vs. Time of day (15 minutes detector data extended to 1 hour).

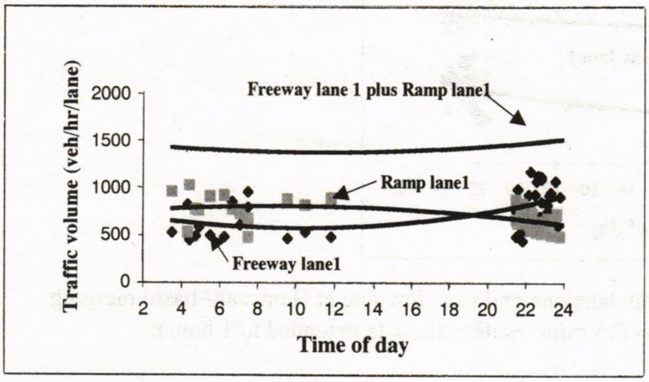

Figure 10. Interaction of freeway lane one and ramp lane one at Hamazaki-bashi merging section vs. time of day (15 minutes detector data extended to 1 hour).

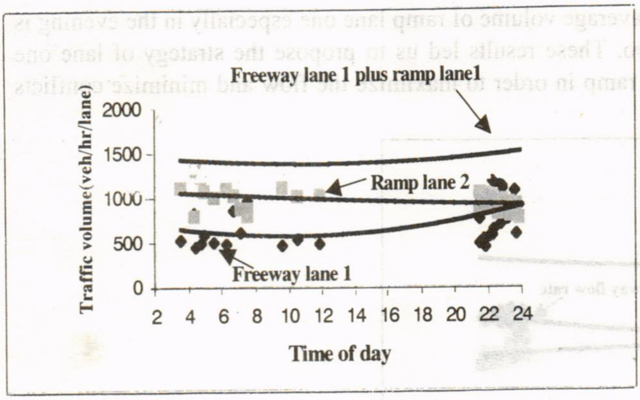

Figure 11. Interaction of freeway lane one and ramp lane two at Hamazaki-bashi merging section vs. time of day (15 minutes detector data extended to 1 hour).

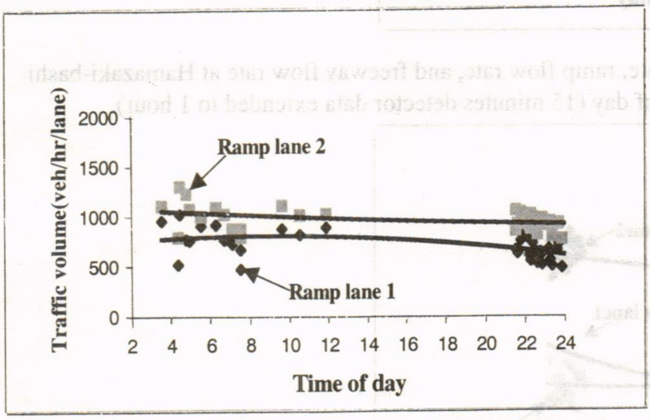

Figure 12. Distribution of ramp lane one and two flow rate at Hamazaki-bashi merging section vs. Time of day (15 minutes detector data extended to 1 hour).

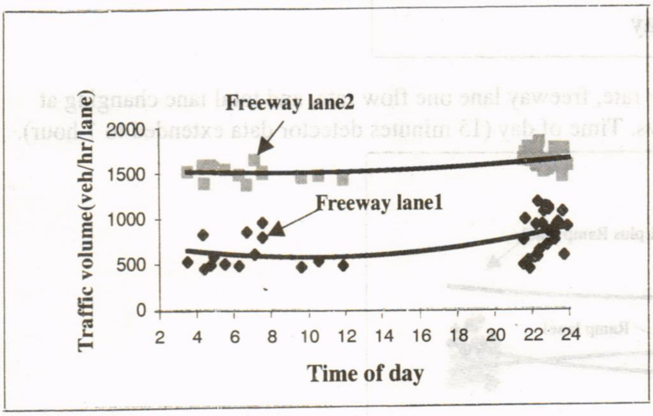

Figure 13. Distribution of freeway lane one and two flow rate at Hamazaki-bashi merging section vs. Time of day (15 minutes detector data extended to 1 hour).

4.4 Capacity of the merging sections

Traffic data from the Horikiri, Hamazaki-bashi, Ikejiri, Kosuge, Kasai, Hakozaki, Ryogoku, and Ichinohashi were collected during periods when queues were forming upstream from the merging sections and downstream were free, so that the capacity could be observed. A typical flow and speed pattern which has been used for capacity estimation and evaluation of a traffic jam at the immediate upstream section as well as downstream section of a merging section is illustrated in Figures 14 to 16. In these Figures, capacity points refer to the capacity definition described in section 3.

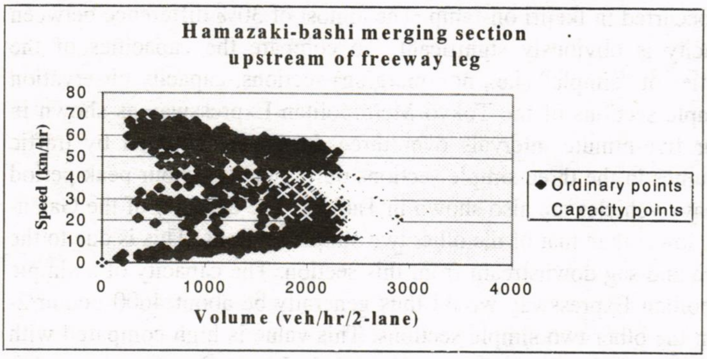

Figure 14. Flow rate speed of freeway upstream of the Hamazaki-bashi merging section (15 minutes detector data extended to 1 hour).

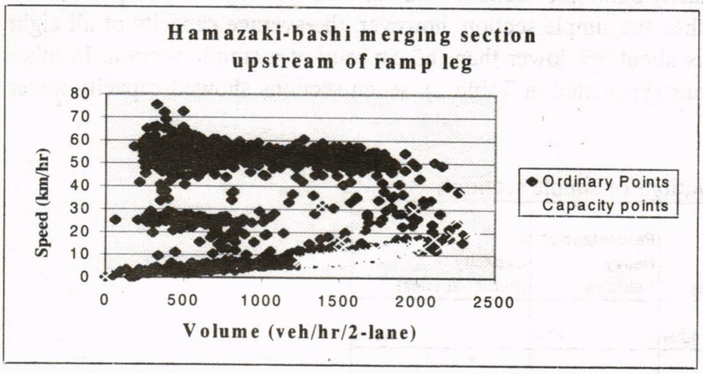

Figure 15. Flow rate speed of ramp upstream of the Hamazaki-bashi merging section (15 minutes detector data extended to 1 hour).

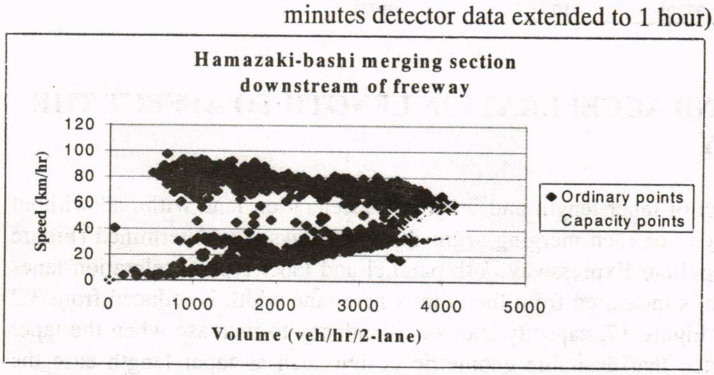

Figure 16. Flow rate speed of freeway downstream of the Hamazaki-bashi merging section (15 minutes detector data extended to 1 hour).

In order to observe the capacity, the time periods more than 15 minutes were selected over seven days when upstream was congested and downstream free. The observed 15 minutes volumes were multiplied by 4 to obtain hourly rates, which were then adjusted to passenger-car units (Pcu) using the passenger car equivalence of 1.5 Pcu/heavy vehicles. No adjustments were made for the restricted lane width, lateral clearance and slope since the speeds were not high enough under capacity conditions. In this study three sets of detector data were used. The first set was collected in 1991, second in 1995, and third set in 1998. The results of average traffic volume in Tokyo Metropolitan Expressway based on detector data for three sets of data are summarized in Table 2. Kasai merging point has maximum capacity of 2458 veh/hr/lane, while the minimum capacity of 1889 veh/hr/lane occurred in Ikejiri on-ramp. The almost of 30% difference between the highest and lowest capacity is obviously significant. To compare the capacities of the merging sections with capacities of "simple" (i.e., non-merging) sections, capacity observation were carried out on three simple sections of the Tokyo Metropolitan Expressway as shown in Table 4. Traffic volumes for five-minute intervals over three days were counted by traffic detectors. Average traffic volumes in the three simple sections during the two-hour peak period and capacities adjusted for heavy vehicles are also shown in Table 4. The capacity of the Gaien-Yoyogi segment is about 15% lower than that of the other two simple sections. This is due to the presence of an S-shaped curve and sag downstream from this section. The capacity of a simple section on the Tokyo Metropolitan Expressway would thus generally be about 4600 pcu/hr/2-lane based on observations on the other two simple sections. This value is high compared with the usual capacity of about 2000pcu/hr/lane for inter city freeway in Japan. Comparing merging capacity with simple capacity, we can see that the capacity of 1973 pcu/hr/lane in Ryogoku is about 14% lower than the capacity of simple section. Although the capacity of 2458 pcu/hr/lane in Kasai is about 7% greater than the simple section, however, the average capacity of all eight sections of 2143 pcu/hr/lane is about 7% lower than the capacity of a simple section. In other words, among the eight sections (Presented in Table 2), seven sections showed capacity lower than 4600 pcu/hr/lane.

Table 4 Capacity observations of simple sections.

Sections	Average Flow for Saturated Two Hours(Pcu/hr/2Lanes)	Percentage of Heavy Vehicles	Capacity (Pcu/hr/2Lanes)
Hakozaki to Ryogoku	4099	27.2	4656
Showajima to Hanada	3864	36.6	4571
Galen to Yoyogi	3770	10.7	3972

5. TAPER LENGTH AND ACCELERATION LENGTH TO AFFECT THE MERGING CAPACITY

In order to consider the effect of taper length and length of acceleration lane with and without zebra marking, average capacity of each merging segment over 7 days was determined (Figure 17 and 18). In Tokyo Metropolitan Expressway both parallel and taper type acceleration lanes have been used (Taper length is measured from the point where lane width is reduced from 3.2 meters). As demonstrated in Figure 17, capacity showed a tendency to increase when the taper length increased. It is expected that desirable geometric design such as taper length ease the merging maneuver process. It seems that by increasing the taper length in congested traffic condition, drivers who were unable to merge early, could now squeeze to merge with freeway vehicles and longer taper could be of great assistance. Moreover, by increasing the taper length, the lateral motion of vehicles is slower and therefore, smoother merging possibly achieved. Figure 18 depicts the capacity with respect to the total length of merging lane with and without zebra marking. The capacities of merging segments were not significantly relative to the total length of merging lane, either with or without the zebra marking. This result was not consistent with those obtained based on free flows merging. J.W. Hess (1963), showed that by increasing the length of acceleration lane, free flow merge, increased. J.A.Wattleworth et al. showed that associated with ramps of low convergence angle and long acceleration lanes, is a reduced mean and standard deviation of accepted gap number. It should be mentioned here that the gap acceptance quality and even gap acceptance capacity "is not equal" to "capacity". However, when drivers are familiar with site, it can be useful to have high capacity even in poor geometric design. C. Kou et al. further demonstrated that the longer acceleration lane length has an insignificant effect upon the freeway and ramp flow rates in the free flow merging condition. Although this study investigated the length of acceleration lane (Includes taper length) ranging from 85 to 145 meters and not covering longer acceleration length often used, however, no effect of the acceleration lane length even in this range on capacity is significant. In addition, in free flow condition the main purpose of acceleration lane is to allow drivers sufficient time to adjust their speed to freeway driver's speed, and find the best gap for merging. However, in congested conditions drivers have to stay in queue until they reach the front, which might be located at the first part of taper length, subsequently merging with adjusted freeway lane. This means that during congested conditions when a driver reaches to the terminal part of the acceleration lane, he noses into the freeway lane and forces the lag vehicle to yield. In this case, the long length of acceleration lane does not show a better usage than a shorter one.

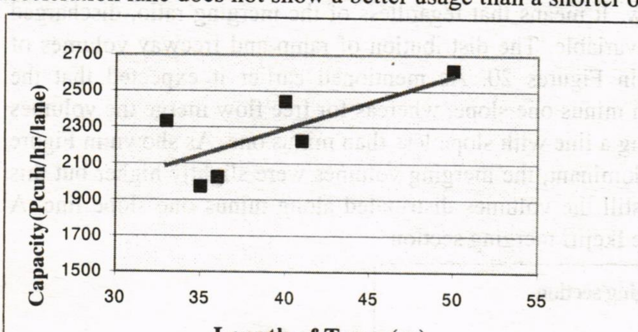

Figure 17. Relationship between taper length and merging capacity (15 minutes detector data extended to 1 hour).

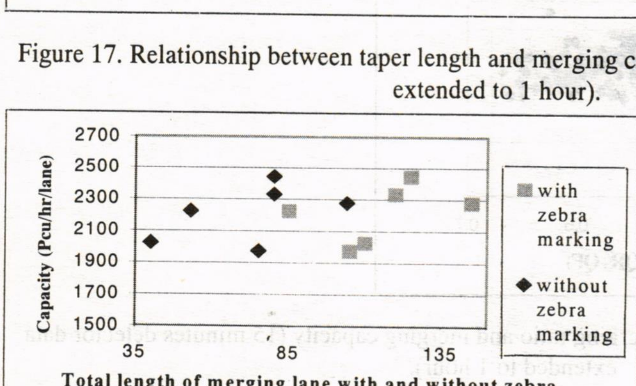

Figure 18. Relationship between total length of merging lane with and without zebra marking and merging capacity (15 minutes detector data extended to 1 hour).

6. MERGING RATIO TO AFFECT THE MERGING CAPACITY

The volume of traffic, which can merge at ramp-freeway connection is dependent on a number of variables associated with geometric and traffic characteristic. One important variable is the relative proportion of two traffic volumes, which are combined to form the merge volume. To eliminate the effect of geometric characteristic on merging ratio, the long period detector data was employed in Hamazaki-bashi and Ikejiri merging segments (See Figure 19 for the case of Hamazaki-bashi merging section). Merging ratio is defined as the ratio of ramp flow rate over ramp plus freeway flow rates. As a result, capacity of merging segments was not significantly related to merging ratio as indicated in Figures 19. The wide range of fluctuation of merging ratio from 0.35 to 0.67 in Hamazaki-bashi and from 0.07 to 0.42 in Ikejiri had no significant effect on merging capacity. With attention to Figure 19, the total discharged flow rate of Hamazaki-bashi bottleneck during congestion is almost constant with 4000veh/hr/2-lanes. One can conclude that when for any reason ramp drivers hesitate to merge (i.e. because of the lack of light) freeway drivers compensate and cause constant discharged flow rate of bottleneck.

J.W.Hess showed, when either freeway flow or ramp flow were dominant the free flow merge volumes were higher than when the two flows approximated each other in volume. It means that, one cannot expect the ease of merging to remain constant, regardless of how the two volumes are distributed. For instance, where 1600 vehicles must merge and all other variables are held constant, it appears easier to merge 400 ramp vehicles with 1200 lane one freeway vehicles than to merge 800 ramp with 800 freeway lane one vehicles. Based on the results of this research, the merging capacity was constant when either merge flow was lower than freeway flow or approximately equal to freeway flow. It means that regardless of the merging ratio, discharged flow rate of bottleneck is almost invariable. The distribution of ramp and freeway volumes of Hamazaki-bashi section is shown in Figures 20. As mentioned earlier it expected that the volumes, distribute along a line with minus one slope, whereas for free flow merge the volumes of ramp and freeway distributed along a line with slope less than minus one. As shown in Figure 20, when the freeway volume was dominant, the merging volumes were slightly higher but this difference was not significant and still the volumes distributed along minus one slope line. A same result has been obtained for the Ikejiri merging section.

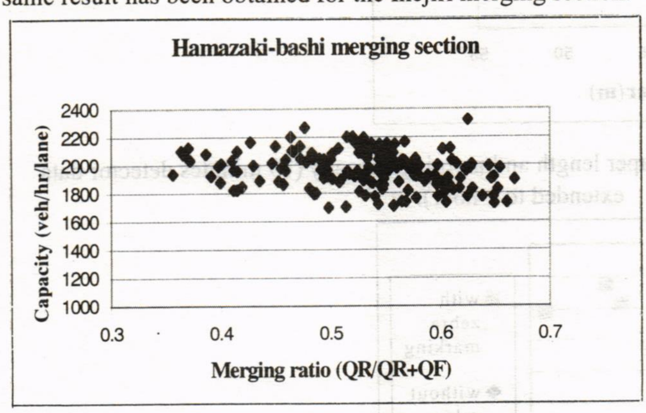

Figure 19. Relationship between merging ratio and merging capacity (15 minutes detector data extended to 1 hour).

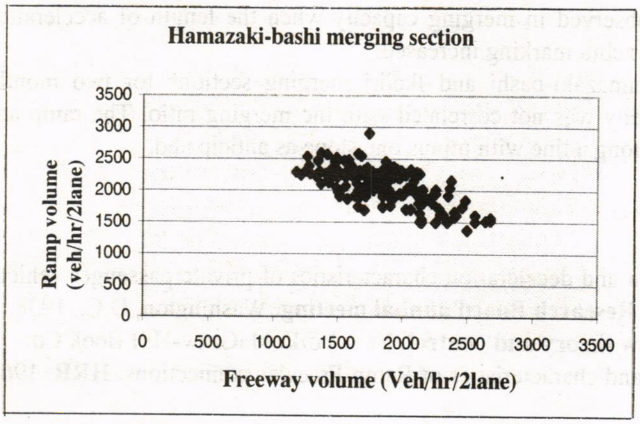

Figure 20. Distribution of ramp and freeway volumes of Hamazaki-bashi merging section (15 minutes detector data extended to 1 hour).

7. RESULTS AND DISCUSSION

Comprehensive traffic data and surveys were collected at several merging sections to investigate traffic behavior and characteristics during merging maneuver in congested traffic situation. In addition, capacity of merging segments (Discharged flow rate of bottleneck) was observed using vehicle detectors in eight merging sections of Tokyo Metropolitan Expressway. The effect of geometric and traffic characteristics on merging capacity were examined. Based on the studies described in this paper, the following conclusions may be drawn connecting the traffic behavior and geometric characteristics during merging maneuver in congested freeway and merging capacity.

1- Comparing the capacity of merging sections with that of a ordinary highway section, it appeared that the merging capacity was lower than that of a ordinary section (e.g., 14% less at Ryogoku section and 7% less as average of all seven sections).

2- The departure flow rate from the queue head, which is the capacity during congestion, is further reduced, as the queue grows longer.

3- Driver's transition of car-following behavior from the free flow mode to the congested flow mode seemed to start when the drivers joined a queue, and completed when they have been in the queue for almost seven minutes in the case of Ryogoku and fifteen minutes at the Ichinohashi interchange. Drivers seem to gradually change their pattern of car-following becoming less sensitive and cautious as they are caught in the queue for longer periods.

4- Specifying and characterizing of three zones could provides enough accuracy in order to explain a driver's decision-making process in merging area under congested traffic situation.

5- Macroscopic aspect of lane changing maneuver and traffic characteristics in zone one and two as well as possible interaction of drivers in the merging area have been discussed. By increasing the traffic volume of freeway lane two, the chance for lane changing of freeway lane one decreases. Therefore, traffic volume of lane one increases, and consequently total lane-changing decreases. Lane-changing maneuver seems easier in the morning and noon rather than evening.

6- In particular in the morning, the average volume of freeway lane one is one third of the volume of freeway lane two, and for the ramp, the average volume of ramp lane one especially in the evening is half that of ramp lane two. These results led us to develop strategies such as closure of lane one of freeway and ramp in order to maximize the flow and minimize accidents.

7- Merging capacity showed a tendency to increase when the length of taper increased. However, no significant differences were observed in merging capacity when the length of acceleration lane either including or excluding zebra marking increased.

8- Observing the capacity of Hamazaki-bashi and Ikejiri merging sections for two months confirmed that the merging capacity was not correlated with the merging ratio. The ramp and freeway volumes are distributed along a line with minus one slope as anticipated.

References

1) Beakey, J. (1938). Acceleration and deceleration characteristics of private passenger vehicle. **Proceeding of the 18th Highway Research Board annual meeting**, Washington, D.C., 1938.

2) Drew, D.R. (1971). **Traffic flow theory and control**. New York: MaGraw-Hill Book Co.

3) Hess, J.W. (1963). Capacities and characteristics of Ramp-Freeway connections. **HRR** 1963, 27.

4) Hess, J.W. (1963). Ramp-Freeway terminal operation as related to freeway lane volume distribution and adjacent ramp influence. **HRR** 1965, 99.

5) Highway Capacity Manual (1985). Special Report 209, **Transportation Research Board**, Washington, D.C.

6) Koshi, M., Kuwahara, M.,Akahane, H. (1989)."Explanation of and countermeasures against traffic congestion." **IATSS research**, Vol. 13, No. 2.

7) Kou, C.-C., Machemehl, R. B. (1997). Modeling vehicle acceleration-deceleration behavior during merge maneuver. **Can. J. Civ. Eng. 24**: 350-358.

8) Pinnell, C., Keese, C. (1960). Traffic behavior and freeway ramp design. **Journal of the Highway Design proceeding of the American Society of Civil Engineering**. September 1960.

9) Polus, A., Livneh, M. (1985). Vehicle flow characteristics on acceleration lanes. **Journal of Transportation Engineering, Vol. 111, No. 6**, 1985.

10) Polus, A., Livneh, M. (1987). Comments on flow characteristics on acceleration lanes. **Transportation Research, 21A(1)**,1987.

11) Rottinghous, B.H. (1974). Urban freeway ramp control. **Proceeding of the summer annual meeting of plning and transport research and computation** (international), Ltd. Univ. Warwich, UK, 1974.

12) Sarvi, M., Kuwahara, M. (1999). Comparative study on evaluation of merging capacity in Tokyo Metropolitan Expressway. **Seisan-Kenkyu, Vol. 51, No 2**, February 1999.

13) Sarvi, M., Kuwahara, M., Nishikawa, I. (2000). A simulation model for evaluation of merging capacity on the Metropolitan Expressway. **Seisan-Kenkyu, Vol. 52, No 2**, February 2000.

14) Sarvi, M., Kuwahara, M., Nishikawa, I. (1999). Macroscopic study on merging capacity in Tokyo Metropolitan Expressway. **Proceeding of the 22nd Infrastructure Planning Conference**, Japan,1999.

15) Sarvi, M., Kuwahara, M., Ceder, A., Morita, H., Nishikawa, I. (2000). Improving the control strategies of freeway merging points using modeling and simulation approach. **7th World Congress on ITS**, Turin, Italy, 2000.

16) Sarvi, M., Freeway ramp merging phenomena observed in traffic congestion. **Ph.D. dissertation**, University of Tokyo, Japan, 2000.

17) Wattlworth, J.A., Buhr, J.H., Drew, D.R., Geric, F.A. (1967). Operational effects of some entrance ramp geometrics on freeway merging. **HRR** 1967, 280.