Empirical Analysis of Congested Traffic Flow Characteristics and Free Speed Affected by Geometric Factors on an Intercity Expressway

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In Japan, much lower traffic capacities occur at S-curves, sag sections, and the entrances of long tunnels on intercity expressways. The traffic capacities at such sections and points were estimated at about 60 to 70 percent that of the basic expressway segments. Oscillating characteristics of traffic flows under congested conditions on urban expressways are already known. However, the traffic flow characteristics on the urban expressways have yet to be analyzed. The traffic flow characteristics under congested conditions, especially the accordion-like actions, the maximum flow rate at bottlenecks, and the relationship between the speed characteristics and geometric factors are analyzed. The data used were collected from 106 detector stations set up in each lane on a 220-km section of the Tomei Expressway. Forty-eight stations were in the upstream direction and 58 stations were in the downstream direction. Three severe bottlenecks on the Tomei Expressway are described. Propagating speeds of the density boundaries between the free and congested-flow regions were estimated. The characteristics of the accordion-like actions caused during the congested conditions on the intercity expressway were almost the same as those of urban expressways. The free speeds in each lane at the detector stations were estimated in the $Q-V_s$ plane. Free speeds were affected by the geometric factors at the detector stations. Multivariate analysis was introduced to quantify the effects of the geometric factors on the free speeds.

In Japan, the first week of May usually has 4 or 5 days of holidays. Many people travel to various places using passenger cars. Therefore, heavy traffic is experienced on the expressways. As a result of the heavy traffic demand, severe congestion occurs at the bottlenecks on intercity expressways.

A much lower traffic capacity exists at S-curves, at sag sections, and at entrances of long tunnels on the intercity expressways. Some researchers have reported that the traffic capacities at these sections and points were from about 2,600 to 2,800 veh/hr per two lanes under congested flow conditions (*1*). These capacities were estimated to be from about 60 to 70 percent that of the capacity at the basic expressway segment under free flow conditions.

However, the effects of these geometric factors on traffic flows have yet to be analyzed. So the geometric factors described earlier affect the capacities and traffic phenomena in the congested flow appearing in the upstream road section at the bottlenecks. The speed characteristics of the traffic flow—for example, the free speed and critical speed represented on the $Q-K-V_s$ plane—may also be affected by the geometric factors.

Factors affecting traffic capacity were described in the American *Highway Capacity Manual* (*2,3*) and in the Japanese *Highway Capacity* (*4*) literature. In Japan, some factors affecting capacity on expressways were quantified. However, some of the geometric factors affecting capacity and running speed on expressways are still unstudied.

Oscillating characteristics of traffic flow under congested conditions on the urban expressways have already been clarified (*5–7*). The capacity analyses and empirical studies about $Q-K(\mathrm{Occ})-V_s$ relationships on urban and intercity expressways have also been analyzed by many researchers and organizations (*3,8–10*). However, in this work few analyses concerning the geometric factors have been carried out, so the relationships between traffic characteristics and geometric factors still need to be quantified.

Koshi and others (*11–14*) have conducted many car-following experiments using test cars on intercity expressways. They have analyzed the car-following behavior at S-curves, sag sections, and at the entrances of long tunnels. The results of these experiments have provided important basic information about the factors that affect the capacity at these bottlenecks.

The traffic characteristics under congested conditions and the relationships between the speed characteristics and geometric factors should be important for the planning and design of expressways and expressway traffic surveillance and control systems.

Basic traffic flow characteristics near capacity and under actual congested condition, especially the capacities at bottlenecks and the accordion-like actions occurring upstream at the bottlenecks, are analyzed. Another objective is to quantify the effect of the geometric factors on free speeds at each observation station and lane on the intercity expressways using traffic detector data.

DATA ACQUISITION

The traffic data used in this study come from the Expressway Surveillance and Control System of the Tokyo First Bureau of Traffic Management of Japan Highway Public Corporation. The system comprised 106 mainline detector stations with

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double-induction-loop traffic detectors (5.5 m distance between loops) on each lane, both in the up- and downstream directions, on a 220-km section of the Tomei Expressway; off-ramp detector stations with ultrasonic detectors (count of volume) at each interchange; and closed-circuit television surveillance cameras in the long tunnels operated from a control center. The accuracy of the double-loop detector is about 95 to 97 percent in volume count. The data analyzed here come from only these double-induction-loop detectors set up at the main line of the expressway.

Forty-eight detector stations are in the upstream direction, and 58 stations are in the downstream direction. The 5-min volume (Q), volume of commercial vehicles, space mean speed (V_s), and time occupancy (Occ) from each detector station were recorded on magnetic tape. A traffic flow record consisting of 10 days during May 1989 was used for the analysis. Some detectors broke down and data from these detectors were eliminated from the analysis. The volume of commercial vehicles were not converted to passenger car units (pcu) in this stage of the analysis. Only percentages of commercial vehicles were calculated both in the up- and downstream directions at each detector station.

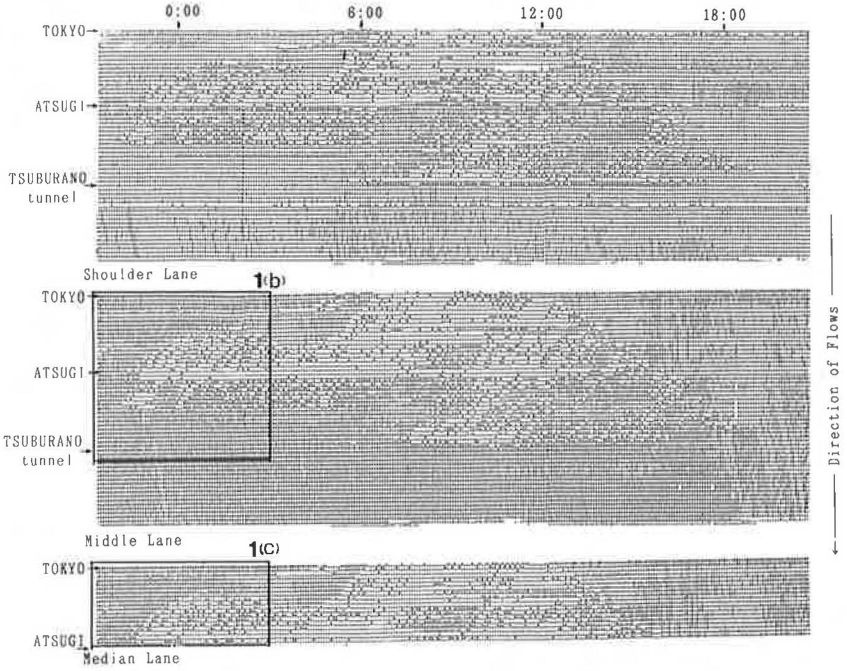
Geometric factor data were also collected with cooperation of the Japan Highway Public Corporation. The geometric factors collected were the gradients and radii at the detector stations, and data concerned with the S-curve, sag, and crest existing within 1.5 km up- and downstream at the detector stations. The 1.5-km distance was equivalent to the running distance when a vehicle runs for about 1 min at free speed.

CHARACTERISTICS OF TRAFFIC FLOW

The heavy holiday traffic occurring in the Tokyo metropolitan area created severe congested traffic conditions on the downward direction of the Tomei Expressway. More than a 70-km slow-moving vehicular line formed during the early morning hours on May 3 in the downward direction of the Tomei Expressway. The head of the slow-moving vehicular line was observed at the entrance of the Tsuburano Tunnel. The percentage of commercial vehicles was from about 20 to 55 percent through 10 days both in the up- and downstream directions of the Tomei Expressway.

Shock-Wave Characteristics near Capacity and Congested Region, and Traffic Flows under Congested Condition

Figure 1 shows congested traffic flow conditions for a 220-km section in the downstream direction on the Tomei Expressway. In this figure, the dots mean values that represent the product of Q and V_s. The traffic conditions are classified by means of the darkness of the dots on the time-space plane (*15*). The darker parts mean higher flow rate and higher speed, and the lighter parts mean lower flow rate and lower speed, indicating that severe congestion has occurred. In the downstream direction of the Tomei Expressway, it is specified that three major bottlenecks exist on the expressway. The first bottleneck is the Atsugi Interchange from where the three-



* Darker dots : Higher flow rate, higher speed
* Lighter dots : Lower flow rate, lower speed

FIGURE 1 Traffic congestion on each lane of the Tomei Expressway (May 1989, downstream direction).

lane roadway drops two lanes (about 35 km from the Tokyo entrance). The second one is the compound geometric section with an S-curve and a sag near Hatano (about 46 km from the Tokyo entrance). The last one is the entrance of Tsuburano Tunnel (about 1.7 km long) at about 68 km from the Tokyo entrance.

Traffic characteristics under congested conditions on urban expressways have been analyzed by the author (*7*) and others (*5,6*). It has been pointed out that traffic flow under congested conditions has some specific characteristics such as the following (*15*):

1. Traffic flow oscillates under congested conditions.
2. Oscillations in traffic flow are not uniform over the congested road section. There are small amplitudes immediately upstream from the bottlenecks. As they propagate upstream, the ripples grow larger, but the wave numbers become fewer in number.
3. The oscillations of the two neighboring lanes become more synchronous as they propagate in the upstream direction.
4. The propagating speeds of waves are almost 18 to 20 km/hr.
5. There are some upper speed limits of the order of the high-speed parts. The speed is thought to be about 45 km/hr on the urban expressways.
6. No specific period prevails in the oscillating characteristics of the traffic flow under congested traffic flow condition.

In Figures 1–3, the fluctuations of traffic flow in the congested regions on the three lanes are synchronized and propagate in the upstream direction at the speed of 17 to 24 km/hr, which is almost the same as the wave speed appearing on the urban expressways (*15*). The oscillating characteristics of congested flow condition, i.e., propagating speed, and periodicity of fluctuations of short-term traffic flow and average speed, have been analyzed by some researchers (*5,6,15*).

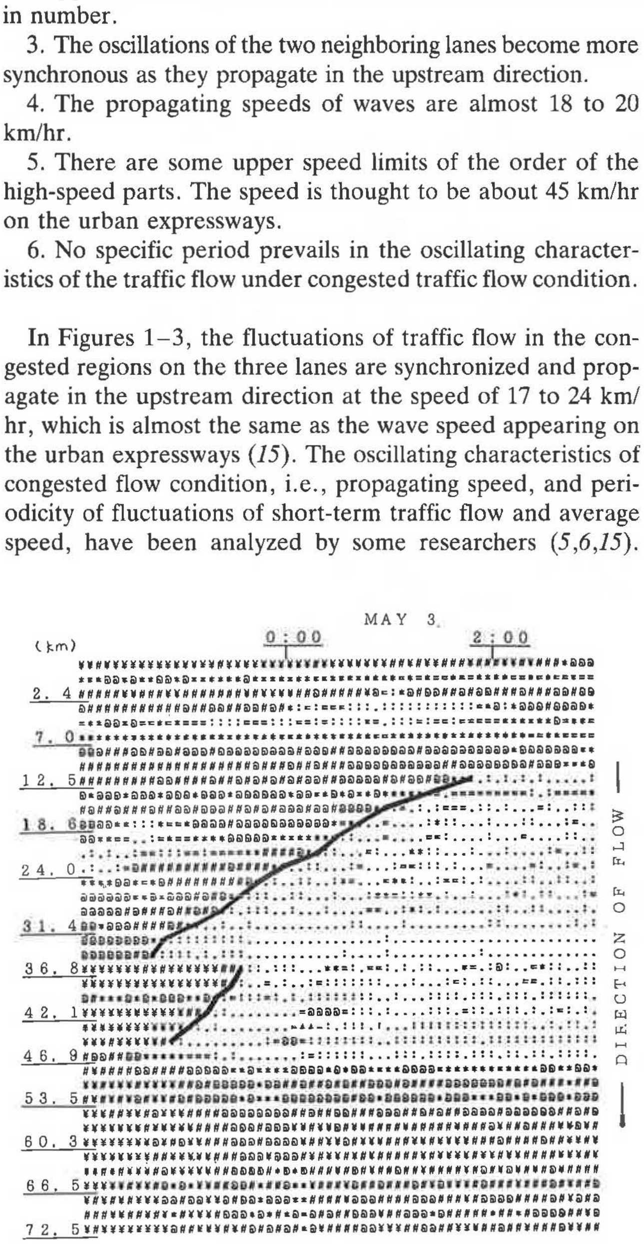


FIGURE 2 Shock wave propagation on middle lane.

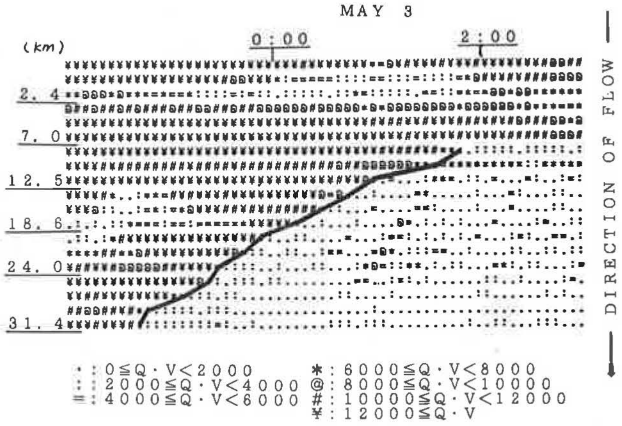


FIGURE 3 Shock wave propagation on median lane.

However, few researchers have dealt with the density boundary characteristics of free and congested regions using field data or observations. In Figures 2 and 3, the propagation of density boundaries between free and congested regions can discriminate. The discrimination threshold used for congested to free flow regions was not flow rate, but the QV value. The QV value, 6,000 veh-km/hr per 5-min interval (* in the figures), is introduced as the threshold. This value was decided on to represent the traffic condition that is 100 veh per 5 min with mean speed for 5 min of 60 km/hr. The average speed of these density boundaries can be estimated to be about 7 to 13 km/hr; it is lower than the propagating speed of traffic flow fluctuations under congested conditions.

The difference in the propagating speed, density boundaries of free and congested regions, and fluctuations of traffic flow in the congested regions may be explainable using the fundamentals of traffic shock wave motion (*15*). In this case, the density boundaries cause the transient conditions from the free to congested transition regions. At the traffic condition just before traffic congestion, the flow rate in the free flow region may be expected to be slightly higher than the bottleneck capacity (Q_{maxI}) (*1*). On the other hand, the flow rate immediately after changing traffic condition (from the free to congested regions) still stays at the higher level (q_{maxI}), but slightly lower than capacity (Q_{maxI}). Then, shock waves are formed by this change in condition of traffic flow (flow rate and density), and propagate with speed C_b shown in Figure 4. On the other hand, the propagating speed C_a of the traffic fluctuations in the congested region is caused only in the congested flow region, and the changes in the flow rates and densities may be larger than the changes caused at the boundary shown in Figure 4. Therefore, the shock wave speed (C_b) may be expected to be lower than propagating speeds (C_a) of the traffic fluctuations in the congested regions.

Volume-Occupancy Relationships

As described, three major bottlenecks exist in the downstream direction on the Tomei Expressway, and the entrance of Tsuburano Tunnel has been already pointed out to be one of the severest-capacity restrictions on the Tomei Expressway as a result of many analyses (*1*). Figure 1 also shows that the entrance

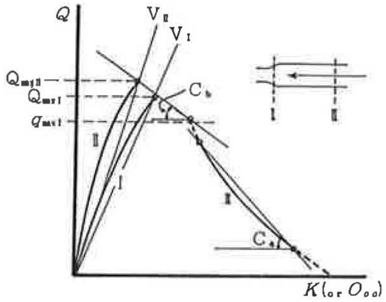


FIGURE 4 Conceptual diagram of shock wave speeds.

of Tsuburano Tunnel is the head of the traffic congestion on the downstream direction of the Tomei Expressway.

Figures 5–8 show the volume-occupancy relationships (*17*) on the shoulder lane immediately downstream of the Tsuburano Tunnel (1.0 km downstream from the exit), immediately upstream of the Tsuburano Tunnel (0.2 km upstream from the entrance), and two points upstream from the entrance, 1.3 and 3.3 km, respectively.

In Figure 3, which shows the volume-occupancy relationship immediately downstream of the exit of Tsuburano Tunnel, the appearance of no congested region contrasts in a striking way with the relationships at the detector stations

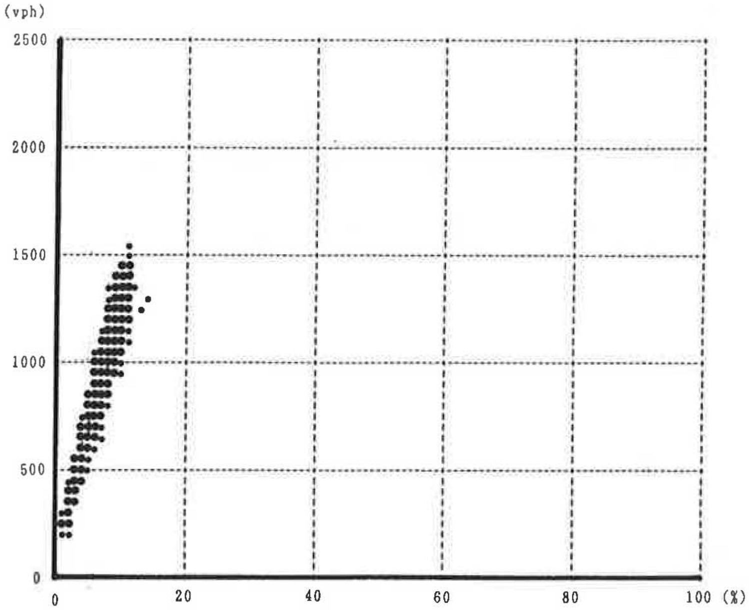


FIGURE 5 Flow rate (5-min) versus time of occupancy at 1.0 km downstream of the exit of Tsuburano Tunnel (shoulder lane).

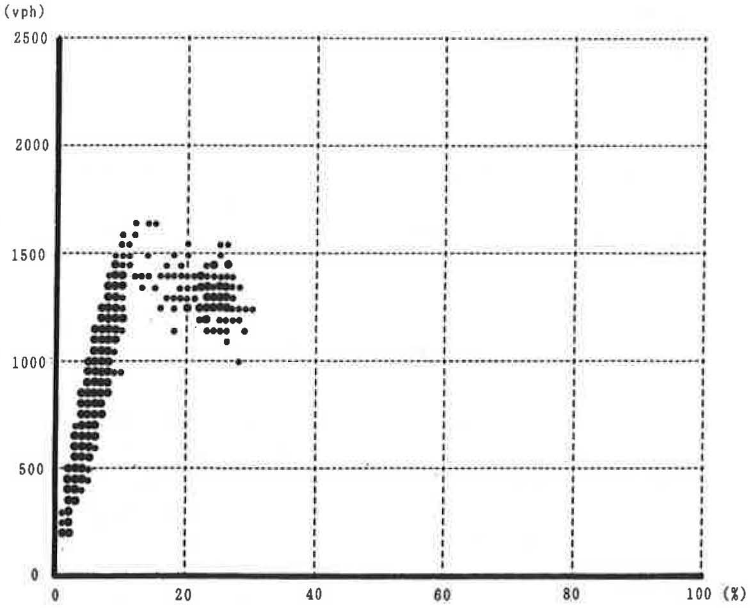


FIGURE 6 Flow rate (5-min) versus time of occupancy at 0.2 km upstream of the entrance of Tsuburano Tunnel (shoulder lane).

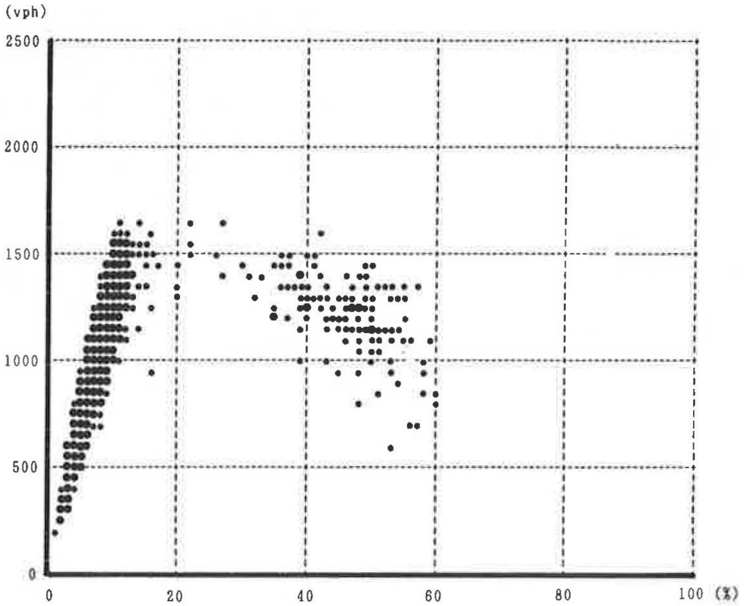


FIGURE 7 Flow rate (5-min) versus time of occupancy at 1.3 km upstream of the entrance of Tsuburano Tunnel (shoulder lane).

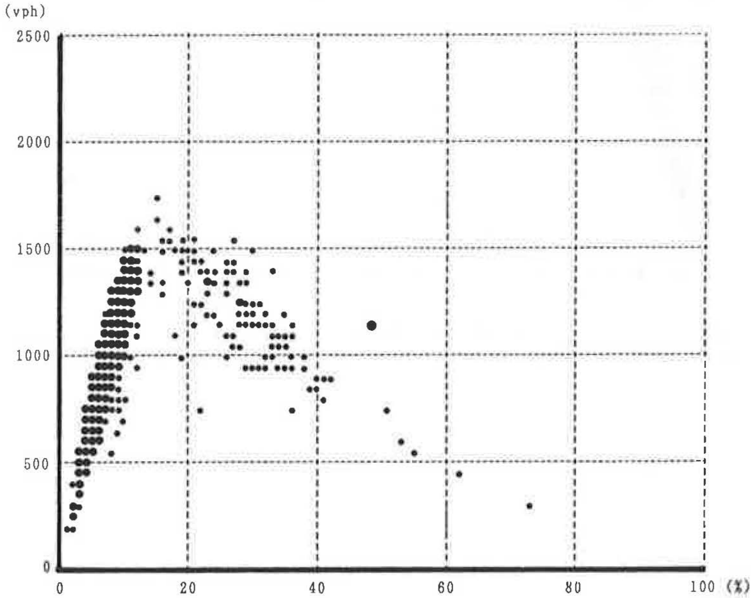


FIGURE 8 Flow rate (5-min) versus time of occupancy at 3.3 km upstream of the entrance of Tsuburano Tunnel (shoulder lane).

upstream of the entrance of the tunnel (Figures 6–8). During restriction of traffic capacity in the long tunnel, the traffic flow that passes through the bottleneck cannot exceed the maximum flow rate of the bottleneck. Therefore, the maximum flow rate appearing in Figure 3 reflects the capacity of the shoulder lane at the entrance of Tsuburano Tunnel.

In Figure 6, immediately upstream of the entrance of the tunnel, discontinuity and discrepancy between free and congested regions are apparent. The maximum flow rates in the free flow region are estimated to be about 1,650 veh/hr per lane on the shoulder lane. The maximum flow rates in the congested region are estimated to be 1,550 veh/hr per lane on the shoulder lane. From Figures 5 and 6, the capacity on the shoulder lane at the Tsuburano Tunnel is estimated to be about 1,550 veh/hr per lane.

Growth of amplitude of traffic fluctuations in congested regions is recognized from Figures 6–8. The tendency of characteristics of growing amplitude in traffic flow fluctuations is the same as on urban expressways, but the upper limit of speeds in the congested-flow fluctuation are significantly larger than that of urban expressways. This difference may be caused mainly by the differences in the design speed, roadway conditions, and regulatory speeds existing between urban and intercity expressways. The regulatory speeds of almost all urban expressways in Japan are 60 km/hr and 100 km/hr for intercity expressways.

ANALYSIS OF THE RELATIONSHIPS BETWEEN FREE SPEEDS AND GEOMETRIC FACTORS

Characteristics of Free Speeds

Free speeds at each lane of the detector stations are estimated using the $Q-V_s$ relationship. Figures 9 and 10 show examples of the $Q-V_s$ relationship in the free flow regions. In these figures, a speed of 60 km/hr is used as the boundary speed between the free and congested flow regions. All the Q and V_s data within the confines of the speed category greater than 60 km/hr are applied to the linear regression. The free speeds are estimated from the intercepts of the Y axis by linear regressions. The free speed is defined when traffic volume is zero. Therefore, the factors that affect the free speeds ought to be the geometric factors at the points and percentages of commercial vehicles.

Figures 11 and 12 show the distributions of the estimated free speed on each lane in the two- and three-lane roadway sections. Differences in mean free speeds clearly exist between the lanes. Figure 13 shows the free speeds at each

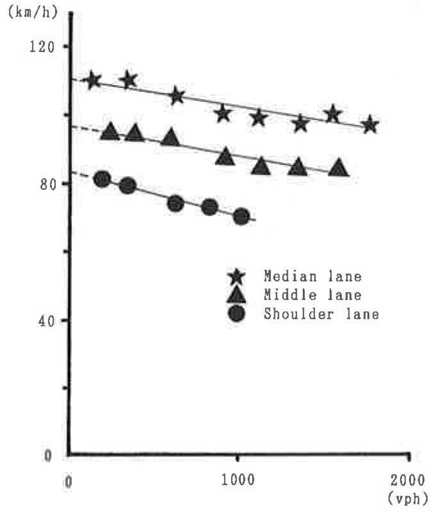


FIGURE 9 $Q-V_s$ **diagram in the free flow region (a three-lane segment).**

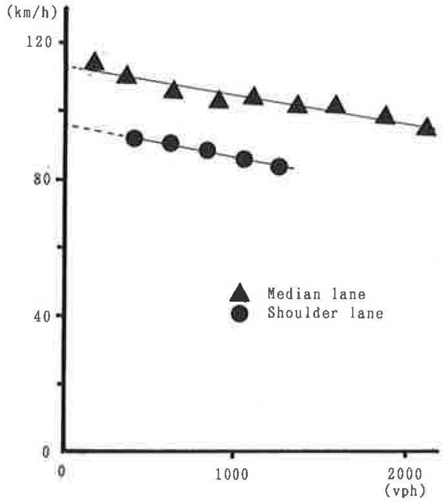


FIGURE 10 $Q-V_s$ **diagram in the free flow region (a two-lane segment).**

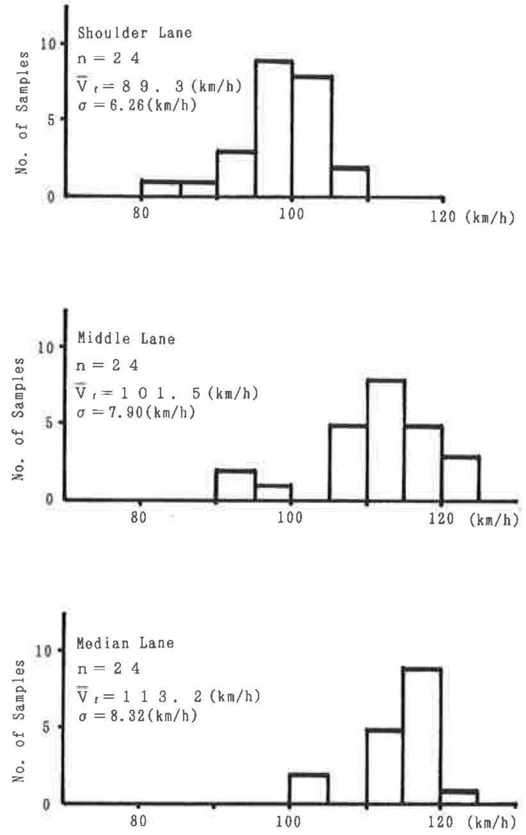


FIGURE 11 Distribution of free speeds in each lane for a three-lane segment in the downstream direction.

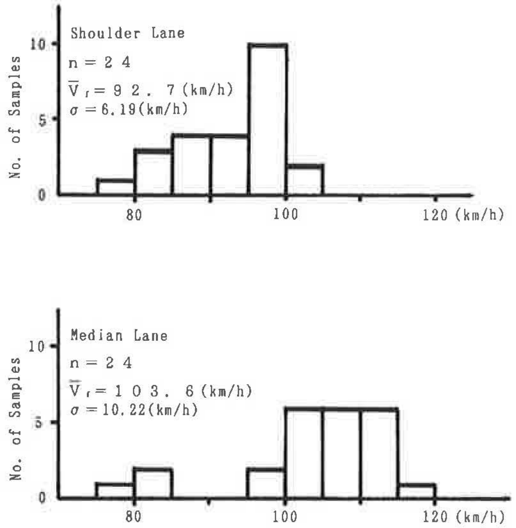


FIGURE 12 Distribution of free speeds in each lane for a two-lane segment in the downstream direction.

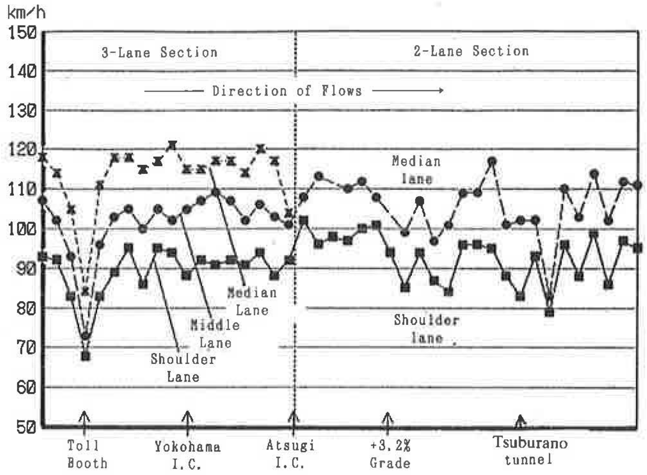


FIGURE 13 Fluctuations of free speed on each lane at detector stations in the downstream direction.

detector station. Significant differences also exist between three- and two-lane roadway sections. From these differences, it would be better to deal with the free speeds on the three- and two-lane roadway sections separately.

As described earlier, three major bottlenecks exist in the downstream direction on the Tomei Expressway. The free speeds at these bottlenecks are lower than the free speeds that appear on the detectors up- and downstream of the bottlenecks. In addition to these bottlenecks, there are some detector stations that have lower free speeds than detector stations on each side of it. Such drops in free speeds seem to depend on geometric factors (for example, upgrades and radii) at the stations.

Figures 14 and 15 show examples of the relationships between the free speeds and typical geometric factors (gradient and curvature radius at the detector stations). According to these figures, the free speeds are obviously affected by the gradients and radii. For example, the steeper the upgrades, the lower are the free speeds. Some of other geometric factors also have an influence on free speeds.

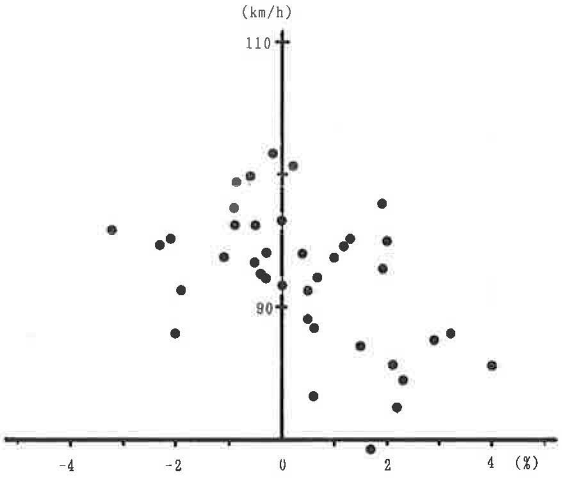


FIGURE 14 Free speed versus gradient in downstream direction on the Tomei Expressway (shoulder lane).

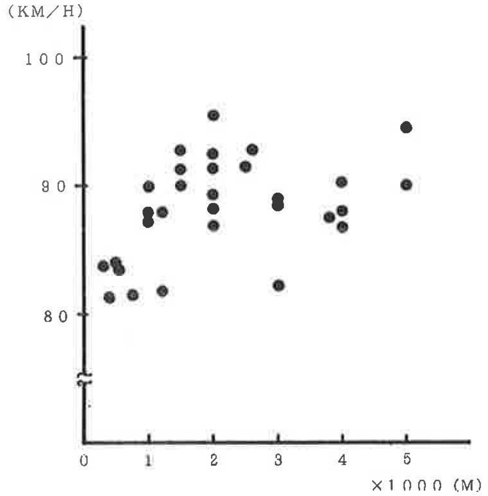


FIGURE 15 Free speed versus curvature radius in downstream direction on the Tomei Expressway (shoulder lane).

Analysis of the Relationships between Free Speed and Geometric Factors using Multivariate Analysis

In the preceding section, it was found that the free speeds are affected by some geometric factors. Next, a model is constructed to explain how the geometric factors and percentage of commercial vehicles affect the free speeds at each detector station on the Tomei Expressway.

The factors used are as follows:

1. The geometric factors at the detector stations.
   a. Radii, and
   b. Gradients.
2. Geometric factors that exist within 1.5 km in front of and behind the given detector stations.
   a. Sum of two radii that form the S-curve,
   b. Distance to the inflection point of the S-curve,
   c. Distance to the bottom of the sag,
   d. Sum of the absolute values of the gradients forming the sag,
   e. Distance to the summit of the crest, and
   f. Sum of the absolute values of the gradients forming the crest.
3. Percentage of commercial vehicles at the detector stations.

As mentioned earlier, the entrance of a long tunnel should be considered as a severe bottleneck to traffic. However, only one long tunnel, the Tsuburano Tunnel, exists in this study section. Therefore, the factors about long tunnels have been eliminated from this analysis.

Several of the geometric factors described do not exist within 1.5 km in front of and behind the detector stations. So, the theory of quantification I, a kind of multivariate analysis method developed by Hayashi (*18*), which corresponds to the multiple linear regression method, is introduced here. Table 1 presents one of the results of the relationship between the free speed and geometric factors. Each factor was categorized, and the degree of influence was calculated as the category weight presented in Table 1. The magnitudes of the range values presented in Table 1 correspond to the partial coefficients of correlation calculated by the multiple linear regression method. The results presented in Table 1 mean that the free speeds on the expressway are significantly influenced by the gradients, radii at the detector stations, and sum of the two radii that form the S-curve existing within 1.5 km downstream of the detector stations.

Figure 16 shows the relationship between the free speeds that were estimated by the model and free speeds estimated by the linear regression described previously. According to this result, the multiple coefficient of correlation was 0.847. Similar results were obtained from other data sets.

The percentages of commercial vehicles are not introduced as significant factors into the multivariate equation. The reasons may be that the classification of percentages are too large (two classes are introduced here, less than 30 percent, and greater than or equal to 30 percent) to be introduced as an influencing factor, and that the percentages of commercial vehicles do not vary between the detector stations.

TABLE 1 CATEGORY WEIGHTS AND RANGES

FACTORS	CATEGORY	NUMBER OF SAMPLE	CATEGORY WEIGHT	RANGE
GRADIENT (%)	i<-3	1	4.524	9.804
	-3≦i<0	8	3.105	
	i=0	1	0.774	
	0<i≦3	13	-1.912	
	i>3	1	-5.280	
RADIUS (m)	R≦1500	9	-3.731	6.867
	1500<R ≦3000	7	1.215	
	R>3000	8	3.135	
SUM OF RADII (m)	R ≦1500	5	-4.407	6.694
	1500<R ≦3000	6	2,287	
	R>3000	7	1.891	
	NON	6	-0.820	

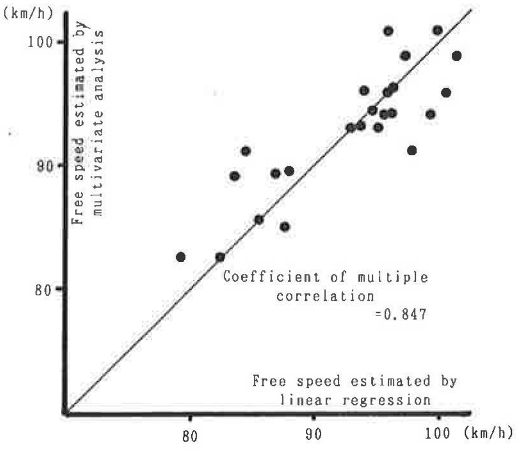


FIGURE 16 Free speed estimated by the model versus free speed estimated by linear regression method for a two-lane segment in the downstream direction (shoulder lane).

The steeper the upgrades (>3 percent) and the smaller the radii (<1,500 m) at the detector stations, the lower are the free speeds. In addition to these results, the two radii that form the S-curve, if less than 1,500 m, and existing within 1.5 km downstream of the stations, adversely affect the free speed at the stations (which is considered to be significant).

SUMMARY

More than 70 km of slow-moving traffic formed during the early morning hours on May 3, 1989, in the downstream direction on the Tomei Expressway. Three major bottlenecks exist in the downward direction on the Tomei Expressway. They are the Atsugi Interchange, at which point the three-lane roadway narrows to two lanes (about 35 km from the Tokyo entrance), the compound geometric section with an S-curve and a sag section near Hatano (about 46 km from Tokyo), and the entrance of the Tsuburano Tunnel (about 1.7 km long, and about 68 km from Tokyo).

The propagating speeds of the density boundary between the free and congested-flow regions were about 7 to 13 km/hr, and these speeds were lower than the propagating speeds of the traffic flow fluctuation in the congested region. The differences in the two propagating speeds can be explained using fundamentals of traffic shock wave theory. Accordion-like actions of the traffic flow were performed in the congested flow. The fluctuations of accordion-like actions of traffic flow on the two and three lanes were synchronized, and propagate upstream at speeds of about 17 to 24 km/hr. Growth in the amplitude of traffic fluctuations in the congested flow was also recognized. These characteristics of traffic flow in the congested flow were the same as those of the traffic flow on the urban expressways. There were some upper limit speeds in the fluctuations of the traffic flow in the congested flow region on the intercity expressways, the same as that of the urban expressways in nature. The maximum flow rate on the shoulder lane at the Tsuburano Tunnel will be estimated to be 1,550 veh/hr per lane.

The free speeds estimated in the $Q-V_s$ plane using the linear regression method have differences between the detector stations and between lanes. The differences seemed to be affected by the geometric factors at the detector stations. A multivariate analysis was applied to estimate the relationship between the free speed and geometric factors. According to the results, the free speeds were affected by the gradients, radii at the stations, and sum of radii existing within 1.5 km downstream at the stations.

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