# Capacity of Sags and Tunnels on Japanese Motorways

BY MASAKI KOSHI, MASAO KUWAHARA, AND HIROKAZU AKAHANE

Since the early 1980s, some of the tunnels and vertical alignment sags on Japanese motorways have been recognized as capacity bottlenecks. Congestion queues have been frequently observed on holidays at these bottlenecks, and the capacity values have been found to range from 2,200 vehicles per hour (vph) to 2,700 vph per two lanes in the same direction, while the expected capacity values were some 4,000 vph per two lanes for passenger car predominant flows. Nothing is mentioned, however, in the current textbooks and manuals of highway and traffic engineering about the possibility of capacity reduction in tunnels and sags.

The purpose of this paper is to describe the facts that have been observed on Japanese motorways and to present the authors' hypothesis on the reason for, and the mechanism of, the low capacities at those sections.

## Macroscopic Aspects

A typical flow and speed pattern of a traffic jam at the immediate upstream section of a sag or tunnel is illustrated in Figure 1. Traffic speed gradually decreases as volume increases until speed suddenly drops when volume reaches a certain level, which is indicated as A in Figure 1. This is the start of congestion. Let us therefore call the volume level A as "capacity before congestion." Traffic volume after this moment is the capacity of the bottleneck because there exists an excess demand in the upstream section in the form of a queue. After the start of congestion the volume decreases to level B, then further to level C. Let us call the values between levels B and C "capacity during congestion."

The value of level A in terms of 5-minute two-lane volume is approximately 250 vehicles, which is nearly equal to 250 passenger-car units (pcu) because congestion takes place on holidays, when passenger cars are predominant. The rate is 3,000 vph/2 lanes, a much lower figure than 4,000 pcu/h/2 lanes of normal sections. The capacity reduction process from level A to level B takes some amount of time, varying widely from case to case, even at the same bottleneck. In the case shown in Figure 1, this transition period was approximately an hour between 5:30 a.m. and 6:30 a.m., whereas it was about two hours in the case shown in Figure 2. The capacity during congestion gradually keeps decreasing down to level C and then increases to level B again towards the end of congestion.

A number of similar results have been obtained at the major bottlenecks on Tomei and Chuo motorways, as shown in Tables 1 and 2. It has been shown that capacities during congestion differ from one bottleneck to another and range between 2,200 and 2,700 pcu/h/2 lanes, substantially lower than the capacity of normal sections.

| Conversion Factors | | |
|---|---|---|
| To convert from | to | multiply by |
| km | mi | 0.62 |
| lux | footcandle | 0.093 |
| m | ft | 3.28 |

## Microscopic Aspects

As traffic volume increases, more vehicles tend to use the medium lane (passing lane). Approximately 60 percent of vehicles in a two-lane section use the median lane when the volume approaches the level of 3,000 pcu/h/2 lanes. This implies that the volume of the median lane is already close to 2,000 pcu/h/lane, which is considered to be the capacity of normal sections. This unbalanced lane use takes place because slow-moving vehicles use the median lane for the purpose of overtaking even slower vehicles or simply because of a lack of lane-use discipline, causing faster vehicles caught in the median lane to form dense and long platoons.

When a platoon in the median lane passes over a sag, the leading vehicles reduce their speed slightly because of the increase of gradient and insufficient acceleration operation. This slight speed drop in the platoon head generates a shock wave, which is amplified as it propagates backwards, resulting in the complete stop of the vehicles in the tail of the platoon.

When traffic volume is as high as 3,000 pcu/h/2-lane level, the next platoon arrives before the stopped vehicles of the previous platoon start up again, resulting in a breakdown in the median lane. Once this happens vehicles upstream in the median lane switch to the shoulder lane in order to avoid stopping. These lane changes cause a sudden increase of flow and disturbances in the shoulder lane, resulting in a breakdown in the shoulder lane. This is the beginning of congestion. The head of the queue stays at the sag after a transition period, although the first shock wave, which triggers the congestion, is generated on the upgrade section in the downstream of the sag.

A head of a queue does not seem to stay exactly at the same spot but instead moves back and forth around the bottleneck. A limited number of observations indicate that shock waves of small speed amplitude take place on the uphill section after a sag even during congestion.

Once the queue has formed, the capacity of the section is determined by the discharge rate at the head of the queue. The discharge rate is relatively high right after the beginning of congestion but keeps decreasing until it reaches level B and then continues to decrease to level C.

In tunnels, speed reduction of vehicles in a platoon head also takes place at the immediate downstream point from the tunnel entrance, probably due in part to the psychological impacts of the dark and narrow atmosphere of the tunnel. The congestion process in tunnels is the same as that of sags. The head of the queue stays immediately downstream of the tunnel entrance.

The departure flow from the head of the queue is characterized by an extremely low rate of acceleration. Figure 3 illustrates an example in which vehicles require 2 kilometers to accelerate from 20 to 60 km/h. In the departure flow, drivers seem not to realize that they are leaving the queue and therefore follow the cars ahead in the same manner as they have been doing in the queue. Drivers finally find that they are already in the free flow when their speeds have been recovered to a level of 70 to 80 km/h.

## Car-Following Model

There are two regions of speed-spacing relationships in the real traffic flow, namely, free flow region and congestion

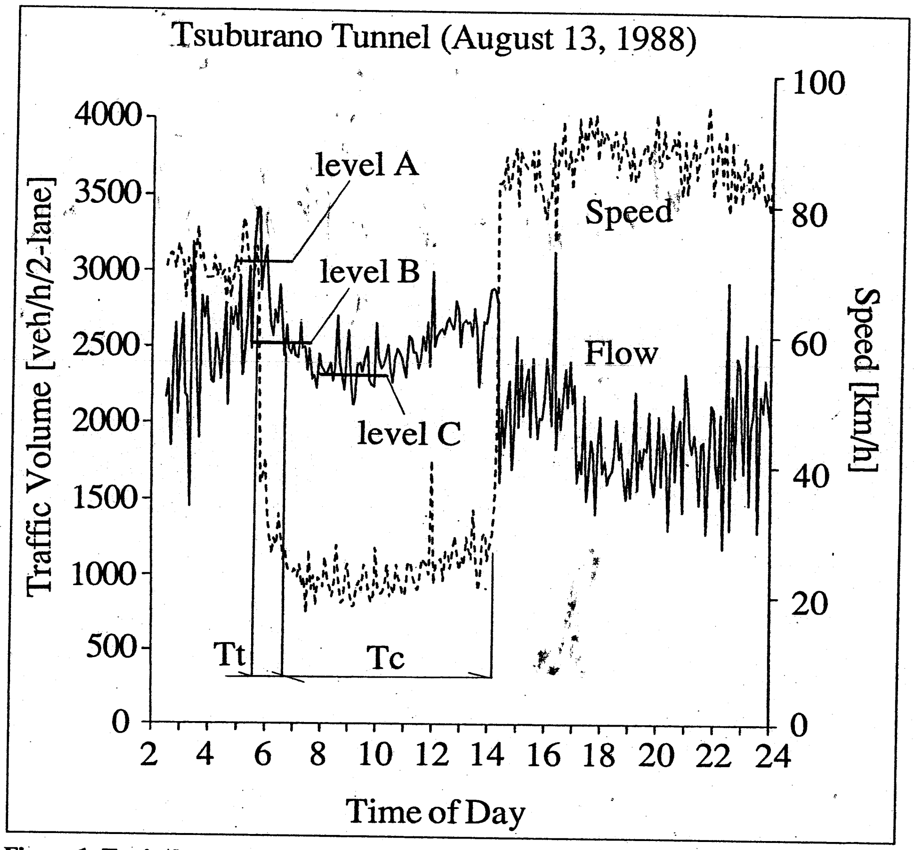



**Figure 1. Typical example of motorway tunnel congestion (5-minute data of detectors at 200 m upstream of the tunnel entrance).**

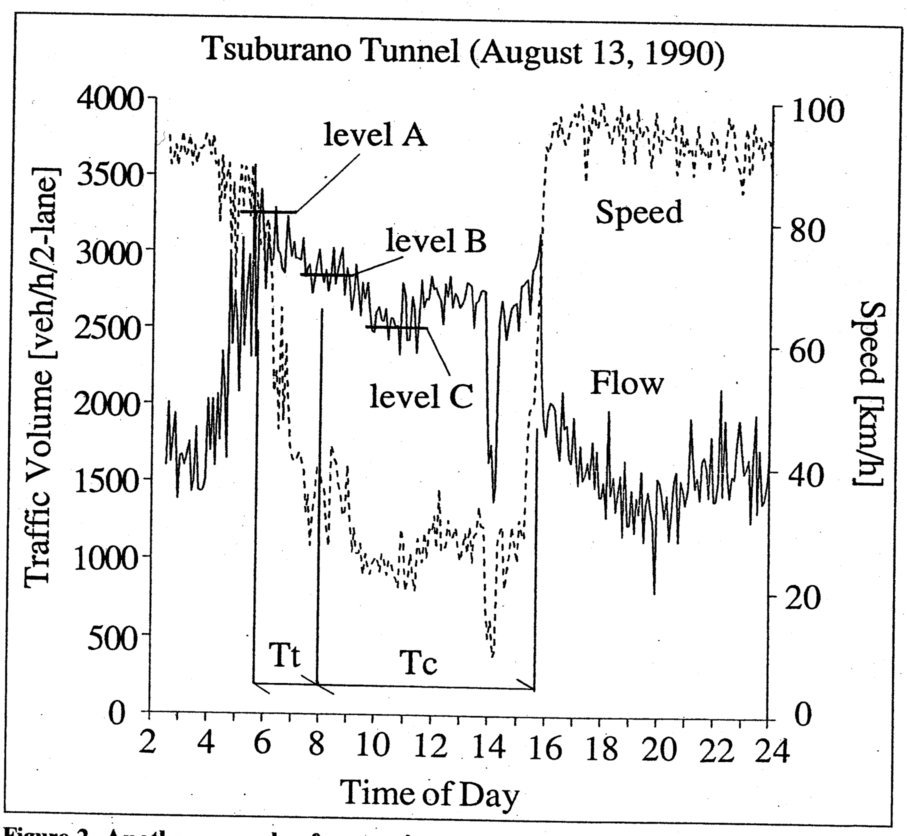



**Figure 2. Another example of congestion at the same site as Figure 1.**

flow region,[1] as illustrated in Figure 4, whereas a car-following experiment gave a relationship as shown in Figure 5. The experiment was implemented in the Tsukuba test course on a circuit of 6.1 km. Each of 29 drivers, who were mostly students randomly selected, was asked to drive in a line following the previous vehicle. The speed pattern of the first vehicle in the line was specified in advance. The speeds and spacings were measured from the video screen recorded from a helicopter. The spacing shown in Figure 5 was then estimated as the average of the followers for each of 2-km/h speed intervals.

The authors hypothesize that drivers in congested flow do not maintain the same level of tension as they do in free flow because they have no hope to overtake and resume their desired speeds in congested flow. In the car-following experiment the drivers were serious enough to maintain the same level of tension in both congested and free flow conditions because they were paid to follow the cars ahead.

A hypothetical mathematical model of car following in congested flow that the author proposed[2] is as shown in Equation 1.

$$\dot{v}(t) = \frac{\alpha \dot{S}(t - T_1)}{S(t - T_1)^l} + \frac{\beta\{S(t - T_2) - f[v(t - T_2)]\}}{S(t - T_2)^m} - \gamma \sin\theta \quad [1]$$

where

$v$ = speed of the follower,
$t$ = time,
$S$ = spacing between the follower and the car ahead,
$T_1$ and $T_2$ = time lags,
$f$ = desired spacing as a function of speed,
$\theta$ = gradient difference at a sag (or a crest), and
$\alpha$, $\beta$, $\gamma$, $l$, and $m$ = constants.

The first term in Equation 1 represents a conventional model of drivers' reactions to the change of spacing, whereas the second term represents a spring action of spacing in which the follower accelerates being "sucked" ahead when the spacing is larger than the desired value. The extremely low rate of acceleration of the departure flow from the queue head is represented mainly by the second term. The departure flow rate

**Table 1. Major bottleneck sags.**

| Motorway | Location (Kilopost) | Gradient (%) | Capacity during Congestion (vph/2 lanes) |
|---|---|---|---|
| Chuo EB | Sagamiko (43) | −3.5–+4.5 | 2,600–2,800 |
| Chuo EB | Saruhashi (65) | −1.3–+2.5 | ——— |
| Chuo WB | Motohachioji (32) | +1.0–+2.7 | 2,500–2,700 |
| Chuo WB | Tsurukawa (52) | −0.3–+5.0 | 2,500–2,700 |
| Tomei EB | Nakai (53) | −3.4–+4.8 | 2,500–2,700 |
| Tomei EB | Matsuda (57) | +1.7–+4.8 | 2,500–2,800 |
| Tomei EB | Isehara (44) | −0.3–+1.4 | 2,500–2,700 |
| Tomei EB | Hadano (47) | −2.6–−0.3 | 2,500–2,800 |
| Tomei WB | Atsugi (40) | −0.6–+2.0 | about 3,000 |
| Tomei WB | Hadano (47) | +0.3–+2.6 | 2,500–2,700 |

**Table 2. Major bottleneck tunnels.**

| Motorway (Tunnel) | Length (km) | Gradient (%) | Horizontal Curve Radius (m) | Capacity during Congestion (vph/2 lanes) |
|---|---|---|---|---|
| Chuo EB (Kobotoke) | 2.0 | +3.2–−4.0 | +5,000 | 2,600–2,700 |
| Chuo EB (Otsuki) | 0.5 | −0.6 | +2,500 | 2,200–2,400 |
| Chuo WB (Otsuki) | 0.47 | +0.6 | −2,500 | — |
| Tomei EB (Nihonzaka) | 2.0 | +2.5–−1.8 | ∞ | about 2,700 |
| Tomei EB (Tsuburano) | 1.66 | +0.5–−1.7 | ∞ | 2,800–3,000 |
| Tomei WB (Nihonzaka) | 2.0 | +1.8–−2.5 | ∞ | 2,600–2,700 |
| Tomei WB (Tsuburano) | 1.69 | +1.7–−0.5 | ∞ | 2,500–2,600 |

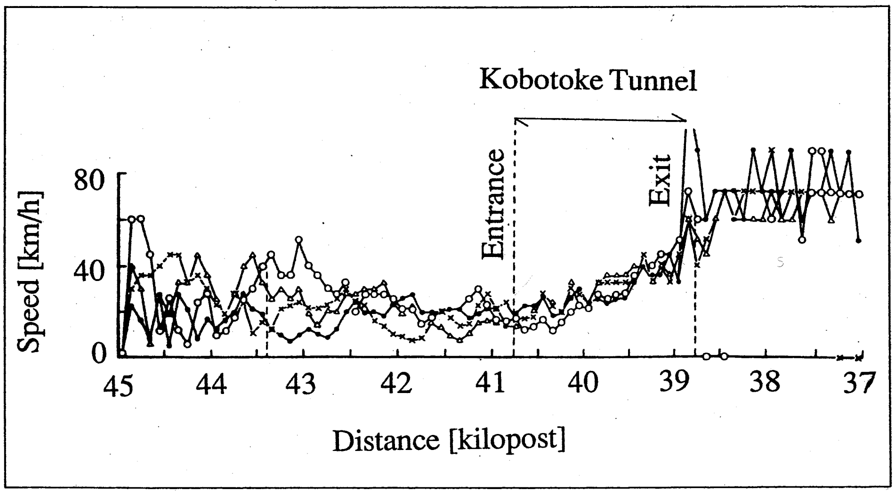


**Figure 3. Speed profiles of floating runs in tunnel entrance congestion.**

from the queue head, which is the capacity during congestion, is also mainly determined by the second term. The third term implies that drivers do not fully compensate for the negative acceleration on upgrade sections.

In contrast to Equation 1, which is for congested flow, the author's model for free flow is as shown in Equation 2,

$$\dot{v}(t) = \delta_1 \frac{\epsilon \dot{S}(t - T_3)}{S(t - T_3)^n} + \delta_2 \frac{\zeta\{S(t - T_4) - g[v(t - T_4)]\}}{S(t - T_4)^p} - \eta \sin\theta + \lambda[V_D - v(t - T_5)] \qquad [2]$$

where

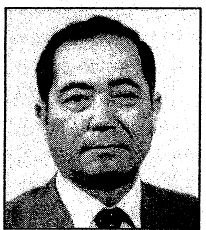
- $v$ = speed of the follower,
- $t$ = time,
- $S$ = spacing between the follower and the car ahead,
- $T_3$, $T_4$, and $T_5$ = time lags,
- $g$ = normal following spacing as a function of speed,
- $\theta$ = gradient difference at a sag (or a crest),
- $V_D$ = desired speed of the follower,
- $\delta_1$ = 0 when $v(t - T_3) \geq V_D$ and $S(t - T_3) \geq 0$
  = 1 otherwise,
- $\delta_2$ = 0 when $v(t - T_4) \geq V_D$ and $S(t - T_4) \geq g[v(t - T_4)]$, and
- $\epsilon$, $\zeta$, $\eta$, $\lambda$, $n$, and $p$ = constants.

The first and second terms do not work for accelerating the follower when actual speed is higher than its desired speed. The fourth term means an additional acceleration element caused by drivers' dissatisfaction with speed when the speed is lower than the desired speed. In case of constant speed that is lower than the follower's desired speed, the fourth and the second terms compensate each other, resulting in steady spacing that is closer than the nominal following spacing. This is another reason for the gap between congested flow and free flow in Figure 4. Figuratively speaking, free flow is a compressed flow or a flow of positive pressure, whereas congested flow is a flow of negative pressure.

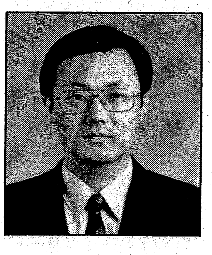
The model shown by Equations 1 and 2 is only applicable when the follower cannot predict the movement of the leader. When the follower can see several cars ahead, the driver can predict how the leader will react. It seems that prediction is also made even when the follower cannot see ahead to the leader. When a large truck approaches the tail of a queue and drastically reduces its speed for a few seconds, for instance, the follower starts predicting that the leader may keep decelerating and come to a complete stop, even though the follower cannot see the situation ahead to the leader. A different model should be developed for car following with prediction.

## Generation and Amplification of Shock Waves

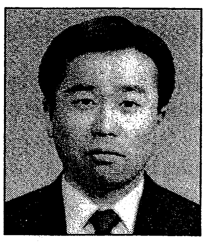
A slight speed reduction of vehicles in the platoon head is amplified as it propagates backwards and the platoon tail

*Masaki Koshi is a professor in the Department of Civil Engineering at the University of Tokyo. He earned his B.Eng., M.Eng., and D.Eng. degrees at the University of Tokyo.*



***Masao Kuwahara,** Ph.D., is an associate professor at the Institute of Industrial Science, University of Tokyo. He earned his B.Eng. at Waseda University, his M.Eng. from the University of Tokyo, and his Ph.D. from the University of California at Berkeley. Kuwahara is an Associate Member of ITE.*



***Hirokazu Akahane** is an associate professor in the Department of Civil Engineering at Chiba Institute of Technology in Japan. He earned his B.Eng., M.Eng., and D.Eng. degrees from the University of Tokyo.*

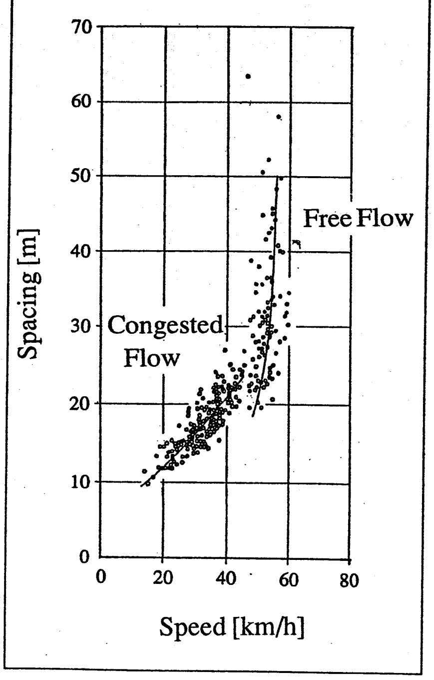




**Figure 4. Speed-spacing in real flow (one-minute average speed and spacing on Tokyo Metropolitan Expressway).**

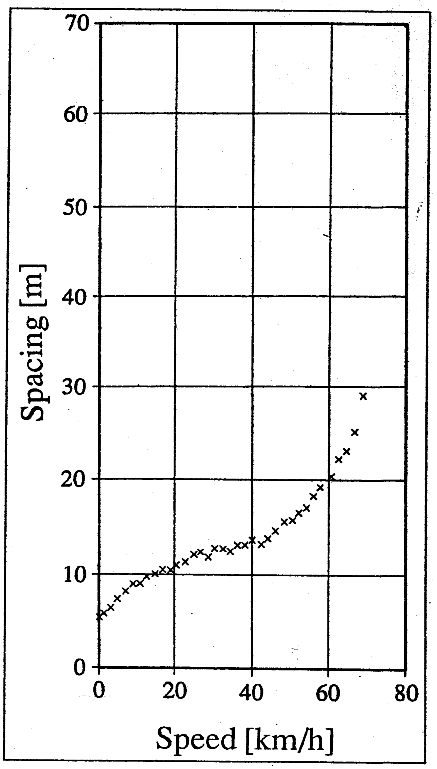



**Figure 5. Speed-spacing in car-following experiment (Tsukuba Experiment).**

comes to a complete stop. This probably takes place because drivers tend to maintain the current spacing even if their speeds are reduced because of the shock wave.

## Transition From Free Flow to Congested Flow

The time period of $T_T$ in Figure 1, during which the flow rate drops from level A to level B, is the transition period from free flow to congested flow.

The drivers seem to switch their car-following behaviors from the free flow manner to the congested flow manner, or Equation 2 to Equation 1, during the time period $T_T$. The transition period $T_T$ varies widely as illustrated by Figures 1 and 2. Figures 6 and 7 show the plots of the departure flow rates during $T_T$ and $T_C$ (from the beginning until the end of congestion) of the cases in Figures 1 and 2 against duration of the time that the drivers have spent in the queue. There are two groups of plots that correspond to the transition period and the steady congestion period. The transition of the driver behavior from free flow to congested flow is completed a little before the time in the queue reaches 10 minutes, regardless of the values of transition period $T_T$, which are one hour for Figure 6 and two hours for Figure 7. Similar results have been obtained for all of several other cases that were examined at two different bottlenecks (a sag and a tunnel). 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 a little less than 10 minutes.

Figures 6 and 7 also indicate that the departure flow rates during congestion decrease as time in the queue increases. Drivers seem to gradually change their parameters of car following to become less sensitive as they are caught in the queue for a longer period of time.

## Impact of Light Condition

A stepwise rise of departure flow rate is seen in the congestion case shown in Figure 8 at about 5:30 a.m., sunrise in August. A group of plots that correspond to this rise is marked in triangles, and the plots before the sunrise are shown in squares in Figure 9. Figure 9 also shows another case of congestion at the same bottleneck during the daytime as indicated by the circles. Figure 9 shows that departure flow rate is higher during the daytime than during the nighttime and is even higher at sunrise when the light condition changes. Facts similar to those shown in Figure 8 have been found in several other cases. At the Kobotoke

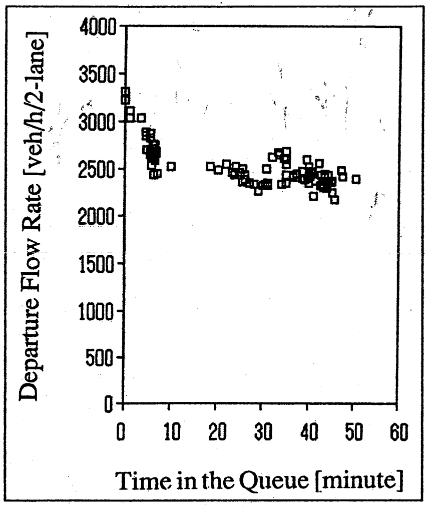



**Figure 6. Departure flow rate vs. time in the queue for the congestion case shown in Figure 1 (15-minute moving average at 5-minute intervals).**

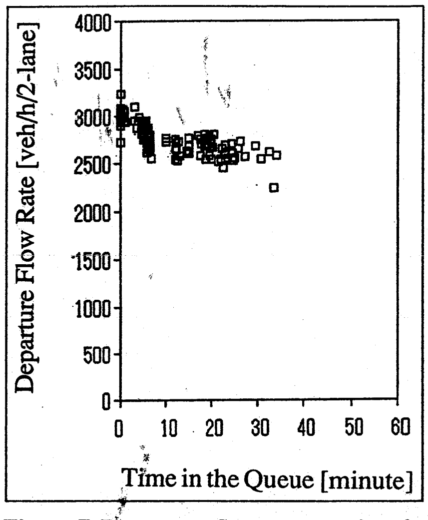



**Figure 7. Departure flow rate vs. time in the queue for the congestion case shown in Figure 2 (15-minute moving average at 5-minute intervals).**

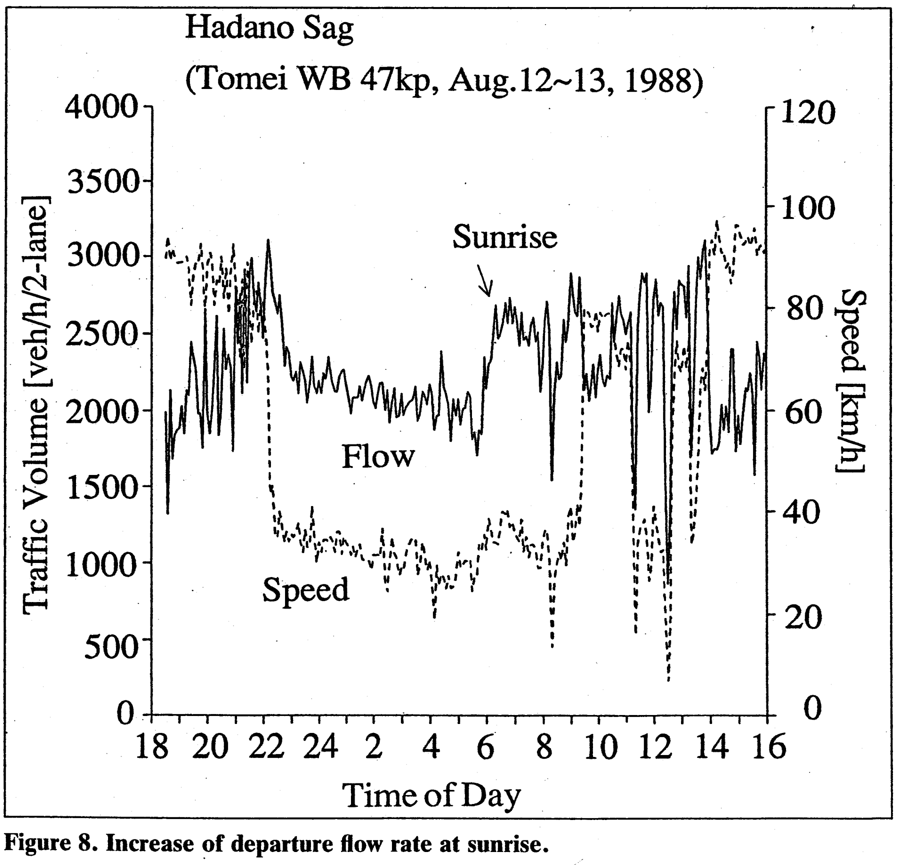



**Figure 8. Increase of departure flow rate at sunrise.**

Tunnel of Chuo Motorway, departure flow rate rises sharply at sunset when the light level becomes brighter in the tunnel than outside. Another related fact is that the departure flow rate of congestion at the Kobotoke Tunnel of Chuo Motorway increased from 2,600 vph/2 lanes to 2,700 vph/2 lanes when the illumination level of the tunnel was raised from 70–90 lux to 150–200 lux on the pavement surface.

There may be two different effects of light condition. The first is the effect of absolute light level and the second is the impact of change of light condition.

## Effect of Weather

Figure 10 compares the capacities of the same bottleneck on a sunny day and a rainy day. The capacities before congestion, as well as during congestion (departure flow rate), do not seem to differ between these two days. No definite conclusion can be made at this time because of the limited cases of rainy day congestion.

## Conclusions

Based on the above data, the authors have concluded the following about capacity at sags and tunnels:

1. Traffic congesion occurs at entrances of tunnels and sags of vertical alignment at traffic volumes that are considerably lower than the capacity values of normal sections.
2. Capacities of tunnels and sags become even lower once a queue forms.
3. Capacity is further reduced as the queue grows longer.
4. Drivers' transition of car-following behavior from free flow mode to congested flow mode seems to start when drivers join a queue and to be completed when they have been in the queue for a little less than 10 minutes.
5. Departure flow rate from a queue is higher in higher light level and is further increased when the light condition changes from a darker to a brighter level.

The results of this research remind the authors of the unique research by L. C. Edie and R. S. Foote on the traffic metering at the entrance of Lincoln Tunnel.[3] The congestion phenomenon in the tunnel must have been caused by the sag in the middle of the tunnel. The increase of capacity obtained through metering must have been equivalent to the difference between levels A and B in Figure 1, which was achieved through avoiding congestion.

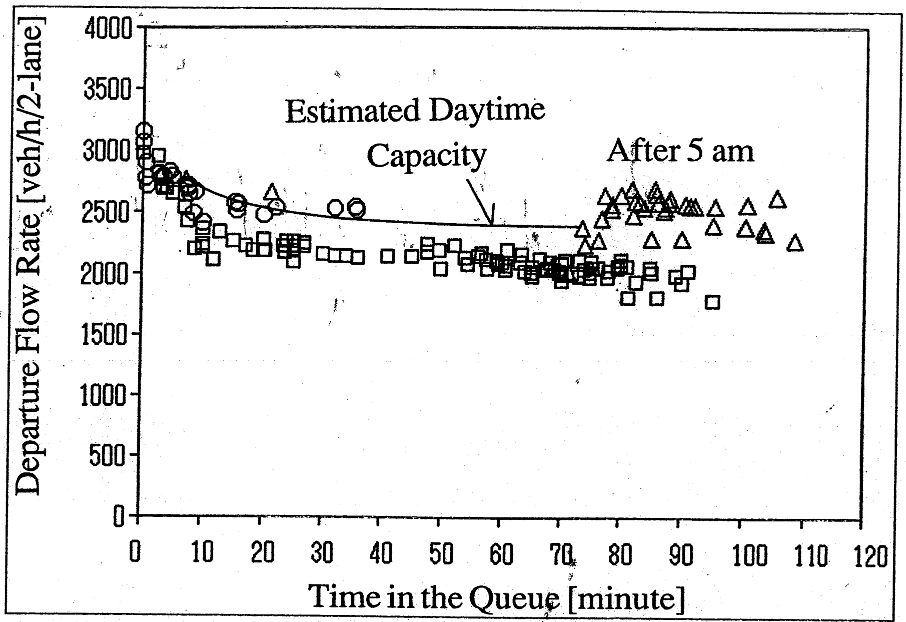



**Figure 9. Comparison of capacity at sunrise with the daytime capacity at the same site as Figure 8 (15-minute moving average at 5-minute intervals).**

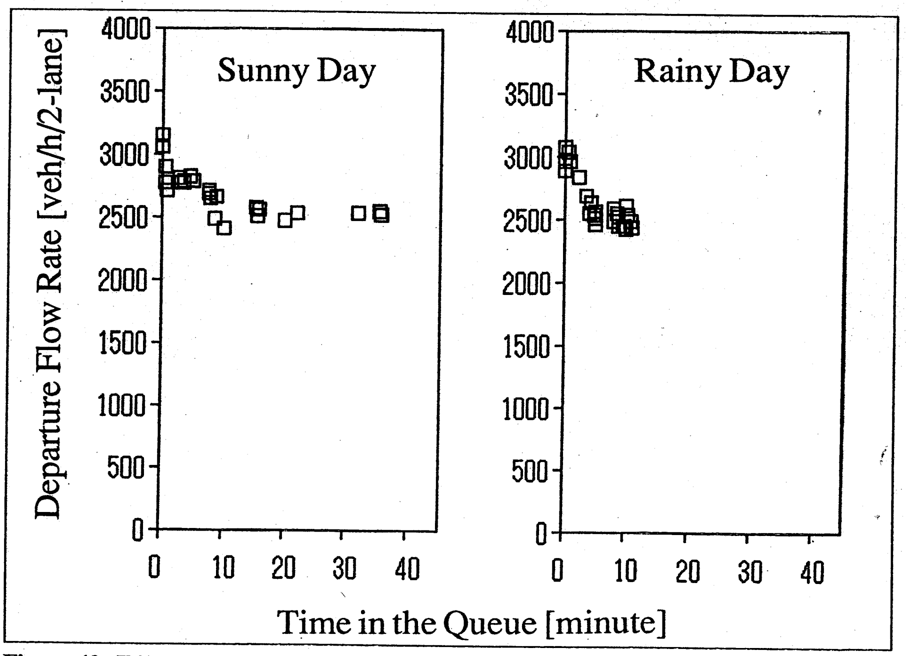



**Figure 10. Effect of weather on capacity of a sag at the same site as in Figure 8 (15-minute moving average at 5-minute intervals).**

## References


1. Koshi, M. et al. "Some Findings and an Overview on Virtual Flow Characteristics." *Proceedings of the 8th International Symposium on Traffic and Transportation Theory.* University of Toronto Press, 1983. pp. 403–426.
2. Koshi, M. "Capacity of Motorway Bottlenecks." *Proceedings of Japanese Society of Civil Engineers*, No. 371/IV-5, 1986-87, pp. 1–7 (in Japanese).
3. Edie, L. C. and R. S. Foote. "Experiments on Single-Lane Flow in Tunnels." *Theory of Traffic Flow.* Amsterdam, The Netherlands: Elsevier, 1961, pp. 175–192.