# SIMULATION ANALYSES OF TRAFFIC CONGESTION ALLEVIATION BY DEMAND SPREADING OVER TIME

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**Abstract:** This study evaluates impacts of demand spreading over time on traffic congestion by the mathematical method and the computer simulation. Impacts of the shifting policy, which eliminates queuing delay at bottlenecks with shifting travelers' departure times without changing their arrival times at the destinations, is not clearly evaluated on the real traffic. So we apply this policy to the cases of Route 19, which is congested by returning trip from skiing, and the Bayshore route of the Metropolitan expressway, which is congested by commuting trips. We handle the case of Bayshore route with a mathematical method and reached the result that congestion may be eliminated by shifting travelers' times. The case of Route 19 is evaluated with the computer simulation and travel time on Route 19 was reduced to 20-40 %. But the shifts are up to 4-5 hours. The amount of the shifts depends on the severity of congestion.

**Key Words:** TDM, Demand Spreading over time, Traffic Simulation

## 1. INTRODUCTION

This study evaluates impacts of demand spreading over time on traffic congestion by the mathematical method and the computer simulation. Based on field observations at Route 19 in central Japan and the Bayshore route on the Metropolitan expressway, traffic conditions of the networks are evaluated before/after the demand control.

Traffic congestion is the major problem because of loss of time, consumption of excessive energy and air pollution. Mitigation of traffic congestion has been desired for a long time.

Traffic congestion has been frequently caused by demand concentration during a peak period. One of the TDM measures is hence demand spreading over time so that the demand does not have a sharp concentration.

In theory, it has been known that queuing delay at bottlenecks can be eliminated by shifting travelers' departure times without changing their arrival times at the destinations.

However, we have not clearly learned impacts of such TDM measure on real traffic on a network. Therefore, we address a question of how much departure time shift is sufficient to substantially eliminate traffic congestion on real networks.

## 2. HOW TO SPREAD

We first explain a theory that eliminates queuing delay by shifting travelers' departure times.

The network considered here, shown as figure 1 has one arterial road and one bottleneck whose service is FIFO (First In First Out) between a departure area and an arrival area. All vehicles depart from some places in the departure area and arrive at some places in the arrival area via this bottleneck. There is no bottleneck elsewhere.

The sharp concentration of demand may cause queuing delay on this bottleneck because the capacity of the bottleneck is limited. Here, we give an example with 2000 veh/h capacity of the bottleneck. All vehicles can pass through the bottleneck without any delay when the

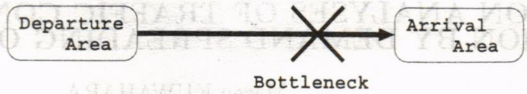


Figure 1: Network considered here

arrival rate at the bottleneck is 2000 veh/h or less. However, when the arrival rate at the bottleneck is 2500 veh/h, 500 vehicles cannot pass through the bottleneck within the hour and they make "queue" from the bottleneck. This queue means traffic congestion and makes "queuing delay", which means waiting time in the queue.

We employed the method of the "cumulative curve", which is useful to visualize a situation of queuing delay on the bottleneck. A graph of the cumulative curve is shown in figure 2, whose horizontal axis indicates time and vertical axis indicates cumulative number of vehicles. The demand is shown on this plane as "Arrival Curve", which shows how many vehicles have joined the queue till the time shown as horizontal axis. Some vehicles cannot pass through the bottleneck at a time they want if the rate of arrival traffic exceeds the capacity, So, "Departure Curve", which shows how many vehicles have passed through the bottleneck, have the maximum slope and may differ from the arrival curve. Therefore, the gap between the arrival and departure curves means that queuing delay occurs on the bottleneck.

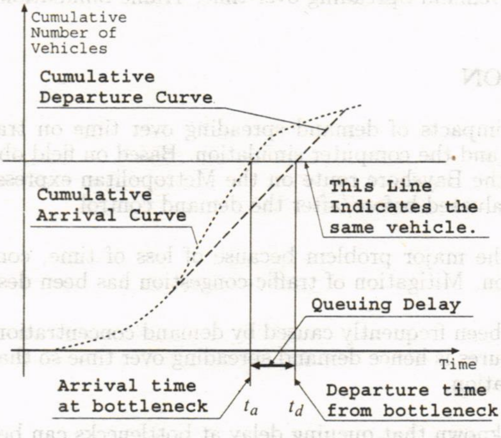


Figure 2: Two cumulative curves, arrival curve and departure curve and how to measure queuing delay from cumulative curves

Queuing delay can be measured from the cumulative curves. Figure 2 shows how we obtain queuing delay of each vehicle. Based on FIFO assumption, no vehicle change their order on the queue and therefore the horizontal line drawn on figure 2 indicates the same vehicle. Arrival time ($t_a$) is indicated with the point where arrival curve and the line intersect and departure time ($t_d$) is the intersection of the departure curve and the line. Under FIFO, Queuing delay ($w(t_d)$) is easily calculated with $t_a$ and $t_d$ as

$$w(t_d) = t_d - t_a. \quad (1)$$

We must eliminate the gap between the arrival curve and the departure curve to eliminate the congestion on the bottleneck. This means that the congestion may disappear if the departure curve and/or the arrival curve are modified to overlap each other. We must note that, however, the slope of the departure curve cannot be larger than the capacity of the bottleneck unless the capacity is improved. So, modifying the slope of the arrival curve is the idea here to eliminate the gap. Figure 3 shows the simplest case. We shift the arrival time of each vehicle to its departure time. The arrival time of each vehicle is then equalized with the departure time and the amount of shifting is the same as the queuing delay which each vehicle receives when no shifting policy is adopted.

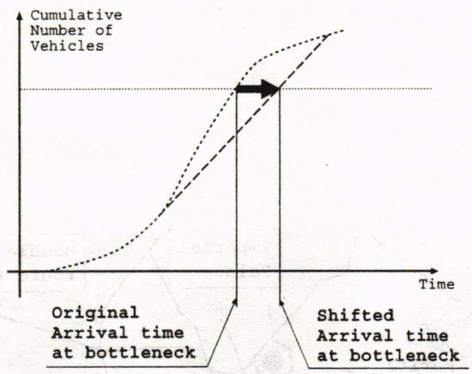


Figure 3: The simplest case of the shifting policy

This policy of shifting has an advantage that "no traveler changes their departure time from the bottleneck." Consequently, they don't have to change arrival times at their destinations even after these trip time shifts are made. Generally speaking, the change of the arrival time may change the value of the trip dramatically. For example, when a worker is late to his/her work, he/she must take severe penalty. Therefore, no change of the departure time from the bottleneck is important to keep each traveler's welfare.

However, this policy of shifting has problems that "we must know the shape of the arrival curve precisely to determine the amount of shifting" and "we must order all travelers to shift their arrival times at the bottleneck. Now we do not have the effective solution to this problem , however, in order to study potential impacts of the shifting policy, we assume that we can know knowledge of all demands of travelers and direct all travelers' arrival times through the bottleneck.

## 3. RESULTS OF STUDY CASES

### 3.1 Bayshore Route on the Metropolitan Expressway

First, we show a simple case on Bayshore route on the Metropolitan expressway, which is shown in figure 4. This case has already been studied with many strategies and some strategies force travelers to change their departure times from the bottleneck (Yoshii, T et al., 1998). Here, we just show the result when the departure times of all travelers are not changed.

This expressway has a bottleneck at Kasai JCT, where Bayshore route and Middle Ring route (often called as "C2") merge, and heavy congestion is often occurred during the morning peak on weekdays.

The network can be replaced by the simplest case which has been shown in figure 1, one-road and one-bottleneck network, with the assumption that the capacity of the bottleneck is not changed over time and we do not controll any vehicles from C2.

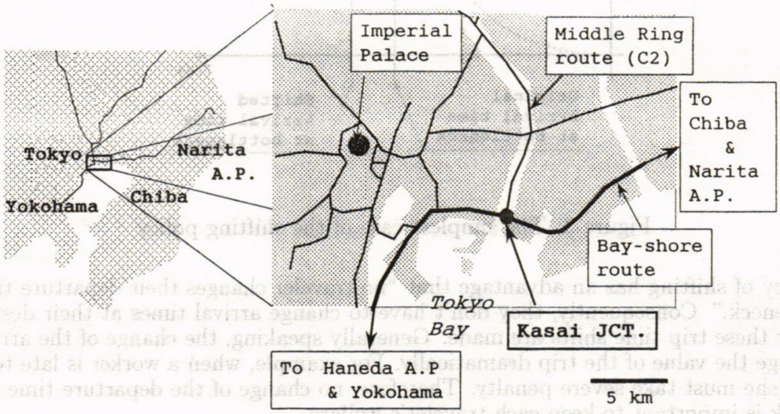


Figure 4: A map of Bayshore route and Kasai Junction

Based upon the data obtained from ultrasonic traffic counters on a day, we drew the cumulative arrival and departure curves as in figure 5. The maximum slope of the cumulative departure curve represents the capacity of the network, which is about 3600 vehicles per hour.

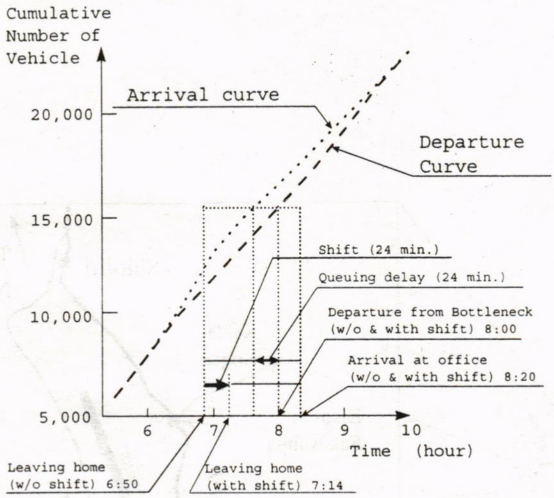


Figure 5: Cumulative curve at Kasai Junction and an example of a traveler

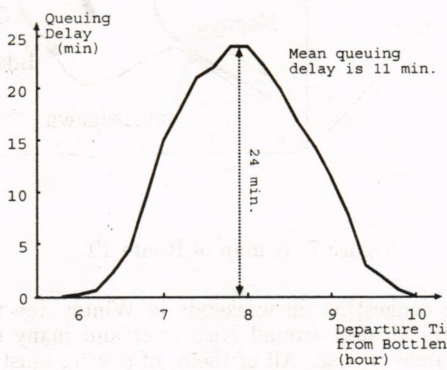


Figure 6: Queuing delay at Kasai Junction

The shifting policy for the demand of this day can be determined very simply from these cumulative curves as explained in the figure 3 and the amount of shifting is the same as the queuing delay shown in figure 6. Let's think a traveler who leaves his/her home at 6:50 a.m., departs from the bottleneck at 8:00 a.m., and arrives at his/her office at 8:20 a.m (see figure 5). His/her queuing delay at the bottleneck can be obtained from figure 6 and is 24 minutes. When we adopt the shifting policy, his/her departure time from the home must be shifted from 6:50 a.m. to 7:14 a.m (+ 24 minutes). The average of the shift is the same as the average of the queuing delay and is 11 min.

We must note that the congestion is disappeared with the shifting policy whose average of the shift is only 11 minutes. And, again, we must also note that his/her arrival time at his/her office is unchanged.

### 3.2 Route 19

Here, we show a complex case on Route 19. Route 19 is the Japanese national highway running along Kiso river in the Chubu district and connects Nagoya and Nagano. (see figure 7). There are many mountains around Kiso river and therefore Route 19 is the only through road around this region.

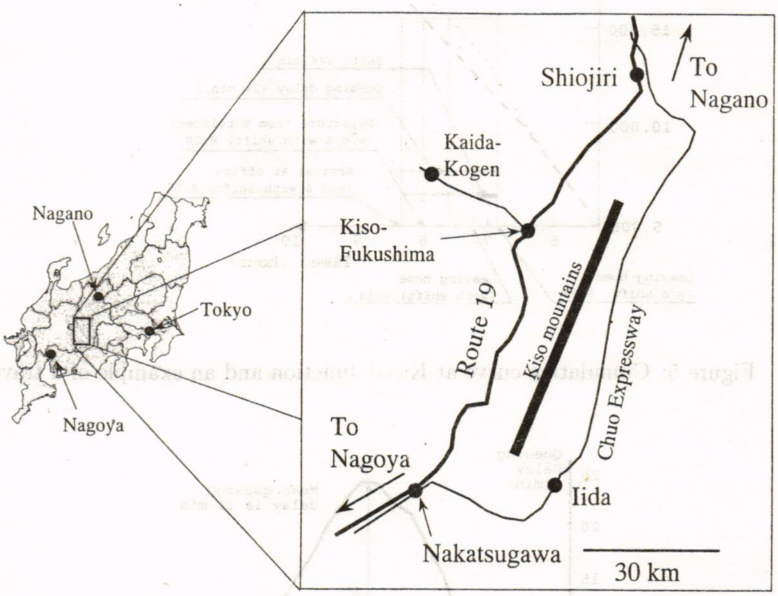


Figure 7: A map of Route 19

Route 19 has heavy traffic congestion on weekends in Winter due to returning trips from skiing. Several ski areas are located around Kiso river and many skiers living in Nagoya and Osaka access to these areas by car. All of them, of course, must return with their cars. Many people tend to leave the areas at evening and therefore a sharp concentration of traffic demand occurs.

They must consume exceeding fuel and endure long driving with repeating of stop-and-go in the congested road. And, this congestion is a serious nuisance for local residents in this area. These are why the strategy of the congestion reduction without affecting the demand of local residents is demanded.

We reproduced real traffic condition of a day with the aid of traffic simulation SOUND (Kuwahara, M. et.al., 1996). SOUND includes density management of traffic flow and the route-choice mechanism. All vehicles choose the fastest route at the time of their choices. The version of SOUND which we used include no traffic signal system. So, we represent the limitation of capacities of signalized intersections with the capacity of the links and the waits at signals with lowering the free flow velocity.

The network used by SOUND is shown in figure 8. Route 19 runs vertically in this figure and some minor roads connect Route 19 with 8 ski yards, Nomugi, Yabuhara, Shinwa, Kiso-fukushima, Chao, Kaida-kogen, Ontake-RP(Ropeway), and Ontake. These ski yards are marked with filled circles.

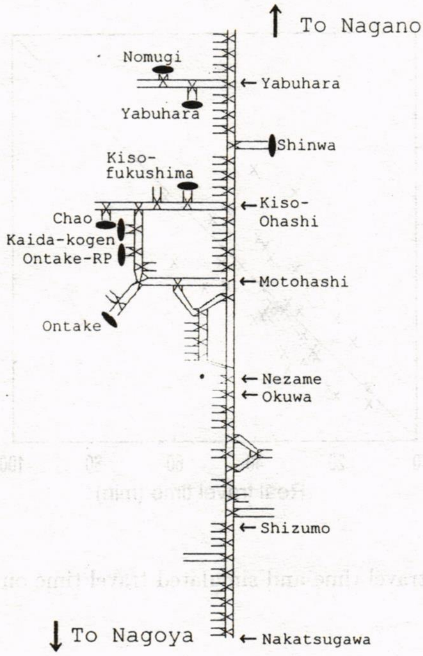


Figure 8: Network for simulation SOUND

We set the OD demand data obtained on a day estimated by a consultant company. Demand is separated into 2 types. One is ski traffic and the other is local traffic.

All traffic simulations must be validated whether they properly reproduce the real traffic condition or not. So, we compared real travel time and simulated travel time on Route 19, where the majority part of the congestion occurs. Real travel times are measured in 12 p.m. - 8 p.m. on February 28, 1999. The sections where measured are Yabuhara - Kiso-Ohashi, Kiso-Ohashi - Motohashi, Motohashi - Nezame, Nezame - Okuwa, Okuwa - Shizumo and Shizumo - Nakatsugawa. To adjust the simulated travel time to real one, the capacities of some significant intersection links were tuned with an auto-tuning program. The real travel time and the simulated travel time on Route 19 are compared in figure 9 and we can confirm that the simulation reproduces the travel time of each section on Route 19 with 13 minutes of root mean square error.

The situation of congestion simulated with SOUND seems to be very serious. Travel time of skiers obtained from SOUND is shown in figure 10. As shown here, some vehicles from ski yard must receive travel time 4-6 times longer in most congested time than free flow. This congestion made by skiers may cause the delay of local vehicles that is shown in figure 11, which shows the travel time when traveling through Route 19. Figure 12 shows average traveling speed of each links. We can see that the congestion spreads through the network and there is major congestion on Route 19 downstream from "Okuwa".

To calculate demand spreading policy, we simplified this complex network to the network whose bottleneck is only one and adopted the point queue model, which neglects the existence of physical queues. As we have already mentioned, "Okuwa" seems to be the most significant bottleneck point. So we calculated how to shifting travelers' departure times with considering just one bottleneck point Okuwa even if travelers pass through other bottlenecks. All other

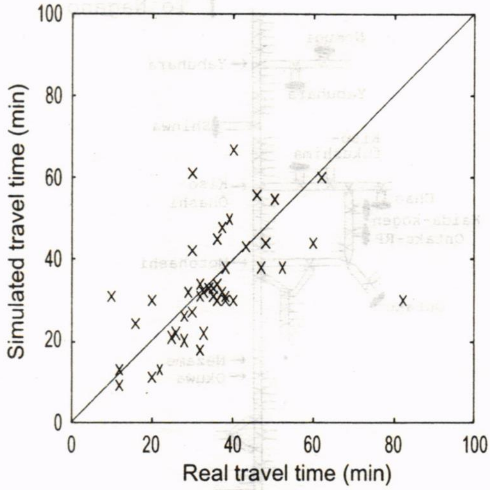


Figure 9: Real travel time and simulated travel time on Route 19

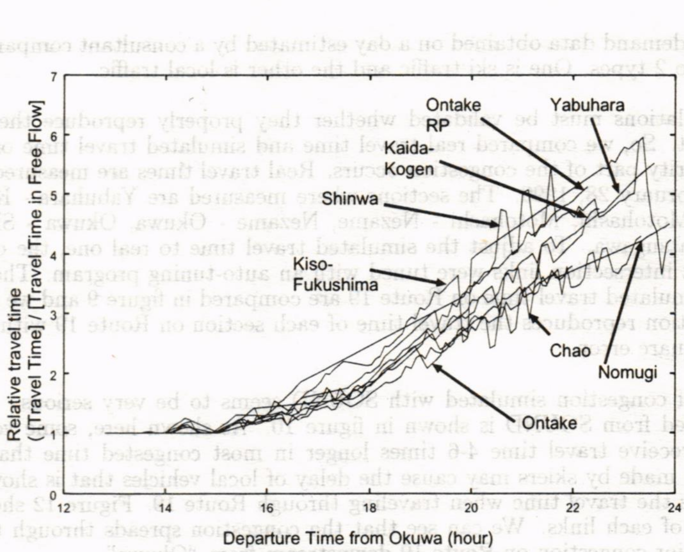


Figure 10: Relative travel time of skiers obtained from SOUND (ski yard - Okuwa)

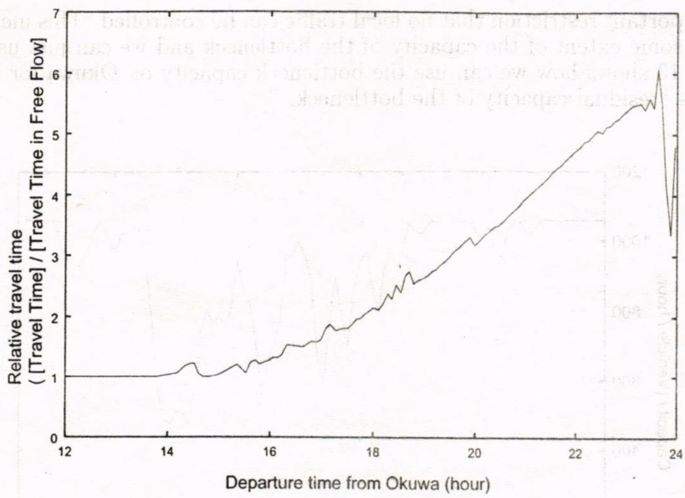


Figure 11: Relative travel time of local vehicles obtained from SOUND (Yabuhara - Okuŵa)

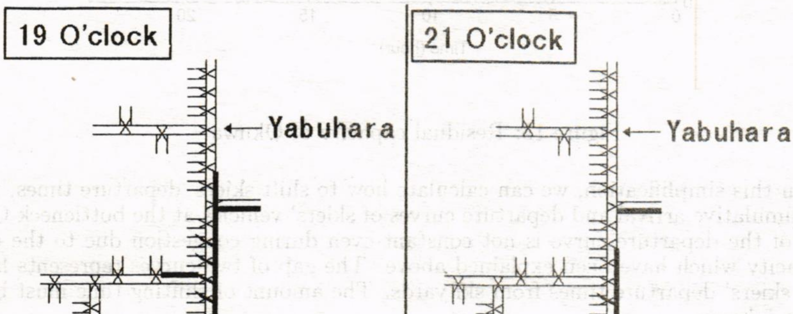


Figure 12: The map which shows average speed of each link when no shifting policy is adopted: Congested (average speed < 20 km/h) links are marked by thick lines

bottlenecks were not taken into account.

There is an important restriction that no local traffic can be controlled. This means that local traffic reserve some extent of the capacity of the bottleneck and we can just use the rest for skiers. Figure 13 shows how we can use the bottleneck capacity on Okuwa for skiers' traffic. We call this as "residual capacity of the bottleneck. "

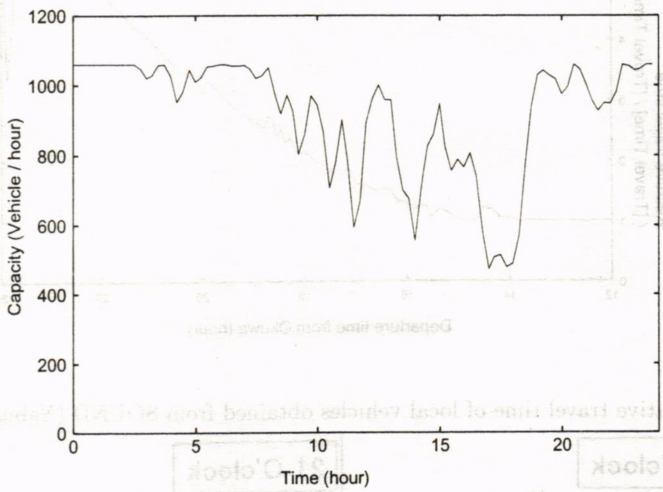


Figure 13: Residual capacity of Okuwa

Based upon this simplification, we can calculate how to shift skiers' departure times. Figure 14 is the cumulative arrival and departure curves of skiers' vehicles at the bottleneck Okuwa. The slope of the departure curve is not constant even during congestion due to the change of the capacity which have been explained above. The gap of two curves represents how we must shift skiers' departure times from ski yards. The amount of shifting time must be very large, up to 5 hours.

We checked this simplification with traffic simulation SOUND and obtained the result. To shift vehicles' arrival time at the bottleneck Okuwa, we made artificial congestion in front of ski yards with altering capacity of links which is connected to ski yards. Vehicles receive some amount of delay due to this congestion and therefore vehicles' arrival times at the bottleneck Okuwa are shifted. Figure 15 shows the relative travel time of skiers. Travel time is decreased dramatically to at most the twice of the free flow travel time. The congestion on Route 19 is also decreased dramatically as shown in figure 16.

This result means that when we attempt this shifting policy to real network system, heavy congestion is effectively mitigated, but we could not take the perfect result where any congestion is disappeared. We think that one of the reason of this is the existence of minor bottlenecks. The shifting policy eliminates the long queue on the network and clear up other bottlenecks which have been buried beneath the long queue. These bottlenecks may disturb for skiers' vehicles to arrive at Okuwa bottleneck on time.

The departure time of each vehicle from the bottleneck Okuwa may be changed with this policy because of the point queue model. Figure 18 shows the cumulative curves of skiers at the bottleneck Okuwa. The cumulative curve without the shifting policy and the one with the policy does not coincide. This means that the vehicles' departure times from the bottleneck Okuwa are changed due to the policy. This is because we adopt a point queue model. The point queue model does not consider the vehicles' merging into the physical queue. The vehicle which merges into the physical queue need not to wait same as longer as the vehicle which joins the queue at the end of the queue. So, queuing delay calculated with the point

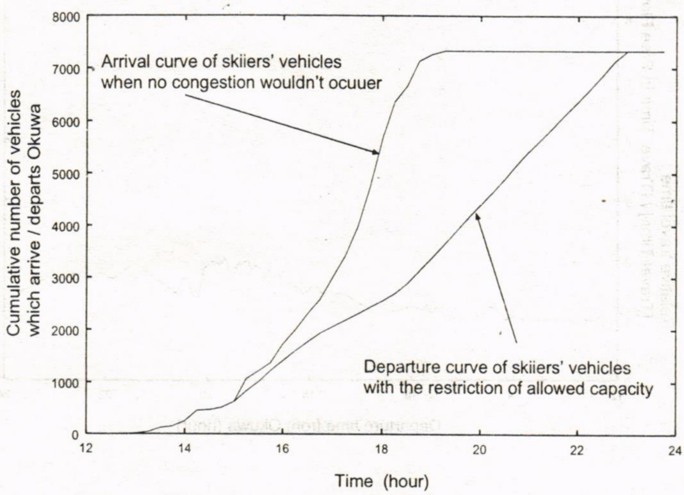


Figure 14: Cumulative curve at the bottleneck Okuwa when no congestion else occur and local vehicles have no queuing delay.

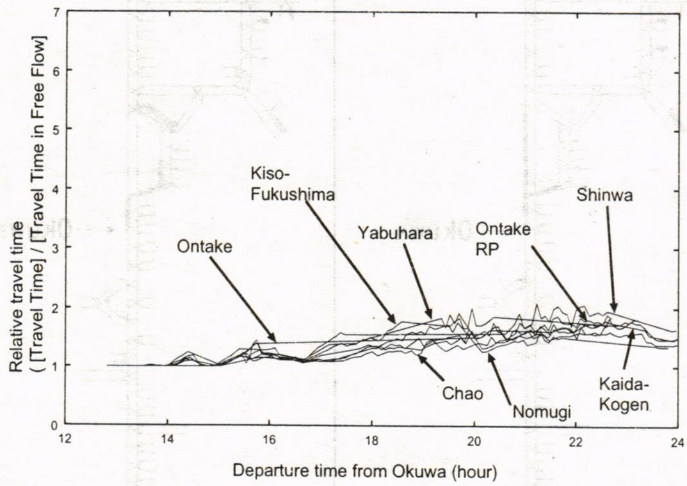


Figure 15: Relative travel time of skiers obtained from SOUND (ski yard - Okuwa)

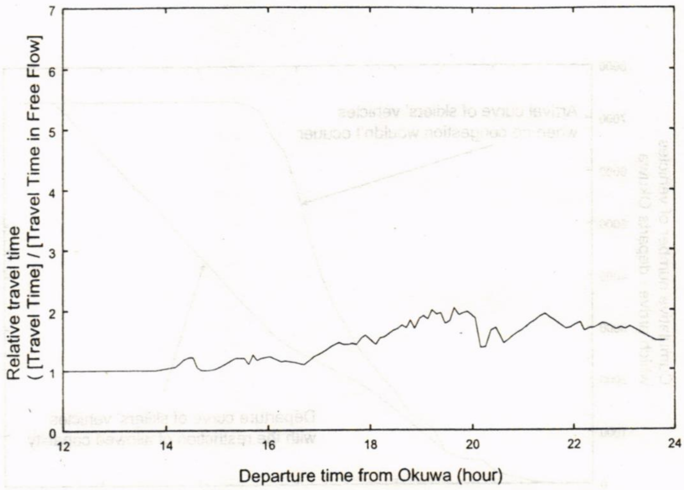


Figure 16: Relative travel time of local vehicles obtained from SOUND (Yabuhara - Okuwa)

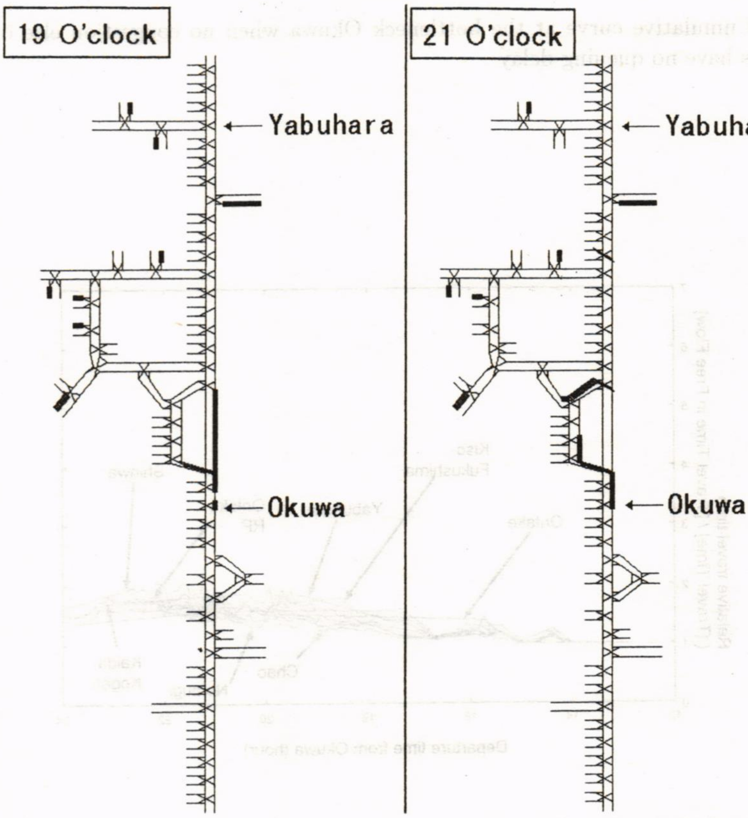


Figure 17: The map which shows average speed of each link when the shifting policy is adopted: Congested (average speed < 20 km/h) links are marked by thick lines.

queue model may differ from real queuing delay and the arrival time at the destination may change with the shifting policy.

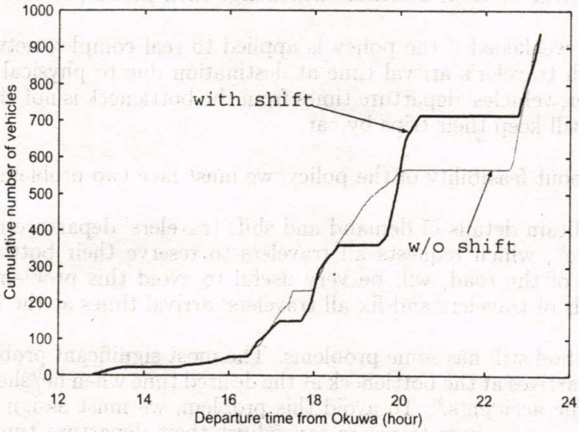


Figure 18: Cumulative curve of vehicles at the bottleneck Okuwa from Kiso-Fukushima

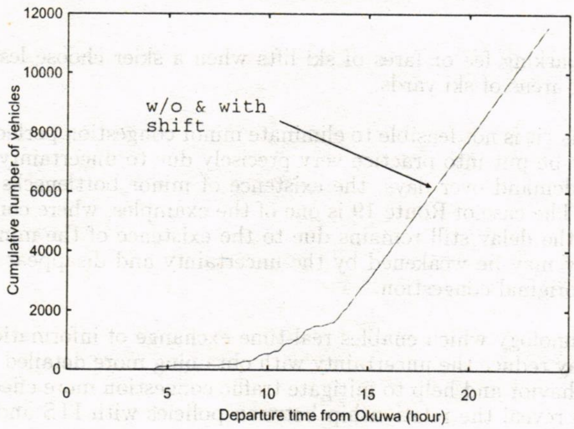


Figure 19: Cumulative curve of all vehicles at the bottleneck Okuwa

However, on the whole, vehicles' departure times from bottleneck Okuwa is not changed. Figure 19 shows the cumulative curve of all vehicles at the bottleneck Okuwa. The cumulative curve without the shifting policy and the one with the policy coincide perfectly.

The calculation performed above neglects the possibility that local demands change their behavior. So, we must tune the "residual bottleneck capacity" and calculate the amount of shifting again when the behavior of local demands changes considerably. And, we must also control the local demands when the demand exceeds the bottleneck capacity.

## 4. DISCUSSION

We have attained the good results that the shifting policy can mitigate traffic congestion effectively and therefore we think that the policy is enough useful to be recommended as one of powerful policies for TDM. We must note that the policy has the big advantage theoretically that travelers' arrival times at their destination are not changed. This means that the policy does not put a severe strain on travelers like some TDM policies which force some travelers to change their arrival times at destinations, change their modes, or cancel their trips.

This advantage is weakened if the policy is applied to real complex networks. It is difficult not to change each traveler's arrival time at destination due to physical queues on complex networks. However, vehicles' departure times from the bottleneck is not changed on the whole and all travelers still keep their trips by car.

When we think about feasibility of the policy, we must face two problems.

One is "How to obtain details of demand and shift travelers' departure times." The "Travel reservation scheme", which requests all travelers to reserve their bottleneck passing times prior to their use of the road, will be very useful to avoid this problem. This scheme can obtain all demands of travelers and fix all travelers' arrival times at the bottleneck.

However, this method still has some problems. The most significant problem is "it is difficult that each traveler arrives at the bottleneck at the desired time when he/she is involved in minor congestion or traffic accidents." To avoid this problem, we must assign travelers' departure times from some points where travelers can adjust their departure times (service areas on freeways, for example) instead of the bottleneck. In the case of Route 19, for example, the scheme we think feasible is:

1) making all skiers to reserve their departure time from parking areas of ski yards when they arrive.

2) discounting a parking fee or fares of ski lifts when a skier choose less popular departure time from parking areas of ski yards.

Another problem is "it is not feasible to eliminate minor congestion perfectly with the policy." The policy cannot be put into practice very precisely due to uncertainty of the system, such as the change of demand over days, the existence of minor bottlenecks, and uncertainty of human behavior. The case of Route 19 is one of the examples, where congestion is alleviated dramatically but the delay still remains due to the existence of the minor bottlenecks. The effect of the policy may be weakened by the uncertainty and disappear if the uncertainty is comparable with original congestion.

However, ITS technology which enables real-time exchange of information between cars and infrastructures may reduce the uncertainty with obtaining more detailed data of vehicle moving and people behavior and help to mitigate traffic congestion more effectively and therefore it is important to reveal the relationship between policies with ITS and human response to them.

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