

## Faster Clearing of Congestion on Expressways using Advanced Adaptive Cruise Control System

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**Abstract:** If the current adaptive cruise control systems(hereafter referred to as ACC) is fitted to vehicles running on expressways, the occurrence of congestion will be relieved by maintaining the appropriate following distance. However, it does not have the function of appropriately controlling starting and following of a vehicle in congestion, so it is considered that once congestion has occurred, ACC is not useful for faster clearing of the congestion. Therefore, in this research an advanced ACC is proposed in which the function of starting and following is added to conventional ACC, and an estimate of the extent to which congestion would be relieved by installing this to vehicles was made based on current traffic data. The results indicate that, for example, when 25% of vehicles are installed with advanced ACC, the congestion volume would be relieved by about 40%. This shows that faster clearing of congestion can be achieved by increasing the use of advanced ACC.

**Key Words:** ACC, ASV, ITS, faster clearing of congestion

### 1. INTRODUCTION

The ACC is a safe driving support service that aims to relieve the driver's operating load and contribute to more comfortable driving by maintaining the set speed and following distance with vehicle ahead, and setting an approach alarm when the vehicle has approached abnormally close to the vehicle in front, etc. In Japan, technical development of ACC is proceeding with the Advanced Safety Vehicle (ASV) project, which aims at the improvement of the safety and convenience of road traffic by increasing the intelligence of vehicles using electronics and other new technologies. At present ACC capable of controlling a vehicle until it stops has been achieved, and it is steadily contributing to safe driving.

Besides relieving the driver's driving load, ACC can maintain the instantaneous following distance constant in accordance with the speed, so it is expected that it will also have the effect of making road traffic smoother. The potential for smoother traffic flow through ACC has been reported in many research studies. In most of these studies the headway and the reaction delay time were arbitrarily set, and for a specific bottleneck the occurrence of congestion and

changes in travel time, etc., in response to changes in capacity were calculated for various rates of use of ACC. In general this research has indicated that by improving the bottleneck capacity as the number of vehicles with ACC increases, it is more difficult to cause congestion, in other words change from a free-flowing to a congested flow state. However, when a greater supersaturated traffic demand arrives at the bottleneck, congestion will occur even if most of vehicles have ACC.

In these circumstances, in addition to being a method to make the occurrence of congestion more difficult, it is necessary to consider methods of clearing congestion once it has occurred, by reducing the starting delay at the front of the congestion and increasing the departure flow rate that reduces after the congestion has occurred. Therefore, the authors have proposed an ACC with the new additional function of smoothly starting and accelerating in congestion, in addition to the existing stopping function. The prompt elimination of congestion that this brought about was quantitatively assessed based on existing traffic data.

## 2. FUNCTIONS OF EXISTING ACC

In Japan most of the auto makers are selling vehicles equipped with ACC, but most of these vehicles are luxury cars, so the number of vehicles equipped with ACC is limited, as shown in Fig. 1 (about 0.7% of the number of domestically produced vehicles). However, in recent years equipping ACC to more popular cars such as small-sized cars and mini-vans, etc., has been increasing, so it is very likely that ACC will become more common in the future.

There are three types of ACC: “high speed ACC” that assumes a good running environment, such as free flow on expressways or highways, “low speed ACC” that assumes low speed or congested areas, and “all speed ACC” which has been commercialized since September 2006, and which controls in both these speed zones as well as down to the stopped state.

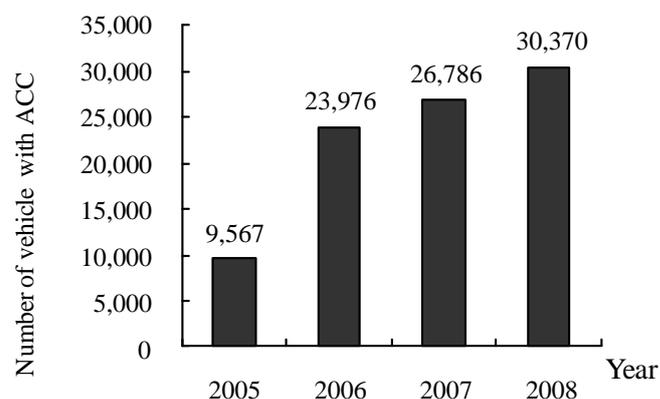


Figure 1 Number of ACC vehicles

### 2.1 High Speed ACC

High speed ACC is applicable to speeds in the range 40 to 100km/h, and can provide the following three types of service (see Fig. 2).

#### a. Fixed speed control function

- If there is no vehicle in front within the sensing area on the same lane that the vehicle is traveling on, the vehicle travels at the set speed.

b. Following distance control function

- If a vehicle is detected in front, the vehicle travels at a reduced speed corresponding to the speed of the vehicle in front in order to maintain the following distance. (Deceleration control)

According to the various manufacturers' operation manuals, at this time the driver can set the following distance in 3 stages.

- When the following distance with vehicle ahead is short, the vehicle speed is controlled so that the appropriate following distance is maintained. (Following control)
- When the following distance in front increases or if the vehicle in front goes away, the vehicle is accelerated to the set velocity. (Acceleration control)

c. Approach warning function

- If the vehicle becomes abnormally close, the driver is warned with an approach alarm.

### 2.2 Low Speed ACC

Low speed ACC is applicable to speeds in the range 30 to 40km/h, but it cannot control down to the stopped state. The services that are possible with low speed ACC include “following distance control function”, and “approach warning function” of the services for high speed ACC. In low speed ACC also the following distance can be controlled in 3 stages.

### 2.3 All Speed ACC

All speed ACC is a service that has a wider operation range, covering all the speed ranges of high speed ACC and low speed ACC, and has the following additional function regarding stopping. However, all speed ACC does not have the function of automatically starting and following when the vehicle in front starts up.

a. Stopping function

- When the vehicle in front decelerates and stops, the vehicle follows the vehicle in front is until it stops.

b. Stop maintenance function

- When the vehicle stops following the vehicle in front, it remains in the stopped state.

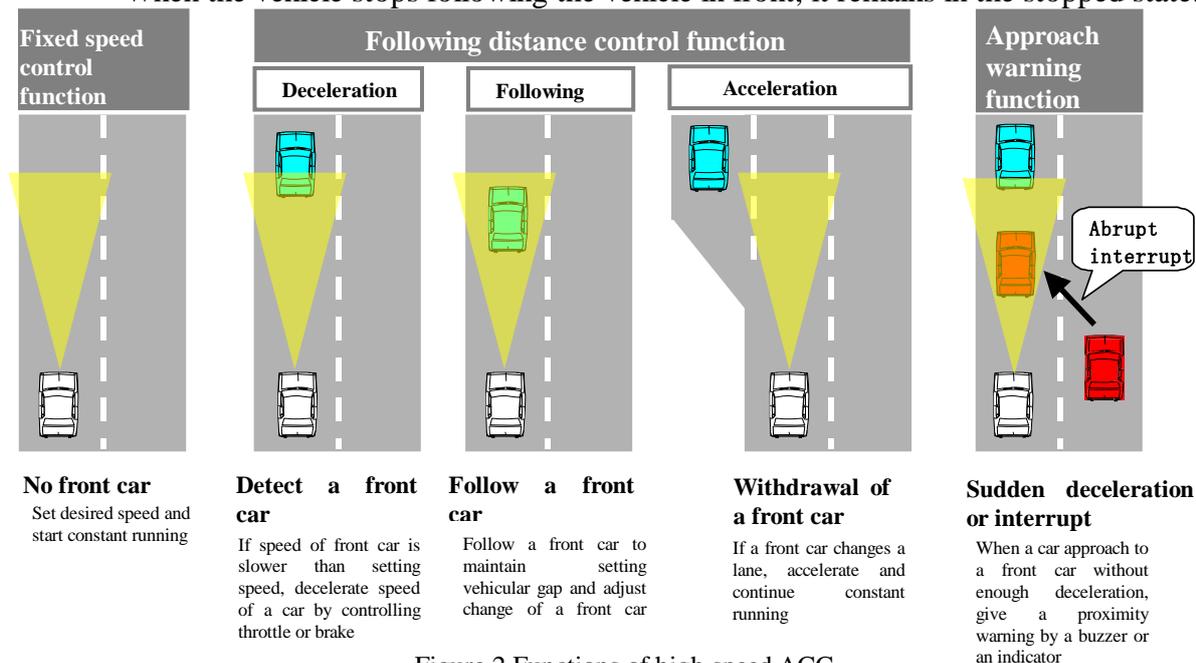


Figure 2 Functions of high speed ACC

### **3. REVIEW OF EXISTING RESEARCH**

Methods of verifying the effect of ACC include the method of evaluation using a tracking model, and the method of evaluation using the concept of a fluid. Using these methods the improvement in capacity, shortening of travel time, and other effects are verified.

In research using the tracking model, it is mainly assumed that headway and the driver's reaction delay, which are described within the tracking model, are reduced by the introduction of ACC, and these are arbitrarily set and evaluated. An example of research in recent years is that of A. Kesting et al, who verified the effect of improvement in capacity and reduction in travel time at bottlenecks where there is a merging lane of traffic. In this it was assumed that the driver behavior varied according to the traffic state (traffic volume). The parameters of the Intelligent Driver Model (IDM), which has been improved by Volkswagen, were set to 5 states, and the spot speed and travel time was calculated for different rates of use of ACC. According to this research, as the rate of usage of ACC increases, the effect of improvement in spot speed and travel time can be obtained. A very interesting effect was that at the level of traffic demand and capacity used in this research (ramp), when the ACC usage rate exceeded 30%, there was a gradual diminishing of the travel time shortening effect. Likewise Suzuki et al(2004) used the GM tracking model (parameters calculated from observation data) to calculate the travel time shortening effect obtained due to ACC when one lane is closed on an expressway. ACC was represented by adjusting the reaction time of the tracking model. This research indicated that in circumstances where the traffic flow is unstable, the introduction of ACC can bring about a more unstable traffic flow, although the reason for this was not given in their paper. Similarly, using a micro-simulation model, M. Minderhoud et al(1999) verified the effect of improvement in capacity at a merging lane. Yoshida et al(1997) modeled the use of ACC in which the distance to the vehicle in front was adjusted as the speed of the vehicle in front was reduced as a sag, and they measured an effect of improved traffic volume.

In research based on the fluid model, Yi, Jingang et al(2006) developed the equations for shock waves in a fluid model, and evaluated the stability of traffic flows. Further, there are papers that indicate that stability in the traffic flow breaks down at the boundary where the state of the traffic flow changes, as in Rajamani, Rajesh et al(2005).

However, in all this research, traffic states changing from free flow to congested flow were evaluated. There has been almost no research on the potential for faster clearing of congestion.

### **4. THE POTENTIAL FOR FASTER CLEARING OF CONGESTION BY IMPROVING THE FUNCTIONS OF ACC**

#### **4.1 The Effect of Current ACC in Improving Capacity**

Table 1 shows the high speed ACC headway calculated based on the following distance provided by each auto maker and the corresponding potential traffic flow rates. According to this table the headway converted from the ACC following distance is clearly smaller than the headway calculated from the basic traffic volume, so as the rate of ACC increases, the number of vehicles passing will decrease. However, assuming a 100% ACC usage rate is achieved, traffic flow rates of 1,440 to 1,500pcu/h per lane will be achieved, so the traffic flow rates in bottlenecks will not be reduced compared with the present rates. On the contrary, ACC promptly reflects the reduction in speed of the vehicle in front, so following distance will be

reduced. Therefore, introducing the appropriate degree of ACC will make it more difficult for shock waves to occur, and in some cases congestion will not be caused by traffic demand. However, traffic flow rates achieved by the introduction of ACC are unlikely to exceed the basic capacity of 2,200pcu/h, so when traffic demand close to this level arrives at a bottleneck, congestion will definitely occur.

On the other hand, in areas having good road structure conditions with no bottlenecks to cause this type of vehicle behavior, traffic flow rates equal to or greater than the basic capacity can be achieved. In such an area if for example a traffic flow rate corresponding to the basic capacity of 2,200pcu/h is achieved, the average headway is 1.6 seconds. However, at this time the distribution of the headway is close to the gamma distribution or Erlang distribution, so more than half of the vehicles travel with a headway less than 1.6 seconds. In other words, considering the scenario that if these vehicles turned off the ACC switch and traveled at their own preferred following distance, the vehicles with greater than average headway will select an following distance to suit the level of each individual vehicle, then it is considered that for non-intersection with no bottlenecks, a state in which the traffic flow rate is greatly less than the basic capacity due to ACC will not arise.

Table 1 Traffic flow rate and headway of high speed ACC

	Vehicle time-headway (sec)	Traffic flow rate (pcu/h)
Level 1	2.4~2.5	1,440~1,500
Level 2	2.0~2.1	1,710~1,800
Level 3	1.6~1.7	2,120~2,250

\* The set following distance for each speed given in each manufacturer's operation manual was converted into time between each vehicle, to this the vehicle length was added to obtain the headway. For calculating the vehicle length time a vehicle length of 4.7m and a speed in the range 60 to 100km/h was assumed. The traffic flow rates are for 100% use of high speed ACC.

#### 4.2 Proposal for Improvement of Current ACC

At sags or tunnels, which cause bottlenecks in single lanes, even though ACC has the effect of increasing the capacity and making it difficult for congestion to occur, as explained in the previous section, when traffic demand exceeding this capacity arrives at a bottleneck, congestion occurs. Further, it is commonly known that after congestion has occurred, the departure flow rate from the front of the congestion reduces together with the time in the queue for the congestion. In contrast, although all speed ACC does not have this function, but if when stopped in congestion, acceleration when starting and tracking could be smoothly carried out, it is likely that the starting delay from the front of the congestion would be reduced and as a result the departure flow rate would be improved, so the congestion could be cleared more quickly.

On the other hand, as stated in section 2, all speed ACC with the stopping function is now available, and ACC has made great progress in the past 10 years. The aim of all speed ACC is to relieve the driving load on expressways and free the driver from frequent acceleration areas over all speeds from high speeds to stationary. However, when considering the path of evolution of ACC from its start with control of following distance up till the present, it can be seen that the next step is to add the function of starting and following. (Hereafter this is referred to as advanced ACC.)

If this advanced ACC is adopted, starting and stopping during congestion will be automatically carried out, so the difficulty of these driving operations will be significantly improved. Also, it

is expected that the occurrence of rear-end collisions at the end of or within the congestion will be greatly reduced. The number of traffic accidents resulting in personal injury or death on Japan's expressways in one year in 2007 was 12,674, of which 36% were rear-end collisions into stationary vehicles in congestion. If this can be improved then expressways will become significantly safer traveling spaces.

Also, in slow moving congestion, drivers' actions in moving forward and the starting delay at the front of the congestion will be corrected, although this depends on the following distance set in the advanced ACC, so the congestion can be resolved quickly without becoming more severe. In addition, if congestion is relieved, the number of traffic accidents will naturally be reduced.

### 4.3 Analysis of the Effect of Introducing Advanced ACC

#### 4.3.1 Specification of advanced ACC (assumed conditions)

Advanced ACC can achieve smooth traffic flow by supporting driver's driving operations of decelerating, stopping, starting, and following operations within congestion, and starting and following operations at the front of the congestion.

However, in order to carry out this type of driving support, from the safety point of view first of all it is necessary to ensure following distance with more margin than at present. However, it is not known what the appropriate distance is, so in this research it has been assumed that the same spacing as at present is provided. In other words, the shortening of the headway by correcting the driver's sluggish moving forward action is cancelled out by this assumption.

On the other hand, ACC is automatically controlled, so it is possible to shorten the driver's reaction time in braking and accelerating (reflection, operation time). This is common to all types of ACC, but in advanced ACC they are also included in the operation support within congestion and at the front of the congestion. However, in the present research, it is assumed that the following distance corresponding to the headway is maintained in congestion, so it is assumed that the acceleration reaction time when starting at the front of the congestion only is shortened, so as to not create a contradiction.

Here the acceleration reaction time at the front of the congestion corresponds to the time from acceleration request until pressing the acceleration pedal (see Fig. 3).

However, insufficient data has been accumulated for the ACC acceleration reaction time, so instead in this research the braking reaction time has been applied.

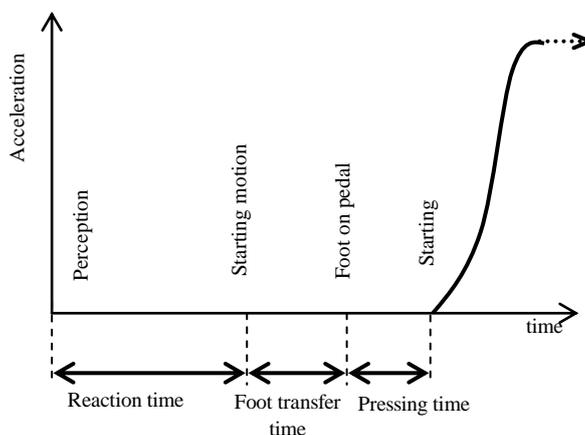


Figure 3 Reaction time

Specifically, in an ordinary car the braking reaction time includes a reaction time of 0.4 seconds, and a foot transfer time of about 0.2 seconds. In contrast, the corresponding values for ACC equipped cars from existing documents are a total of 0.2 seconds, so a shortening of 0.4 seconds is possible. It is considered that the foot transfer time is the same for both ordinary cars and cars equipped with ACC.

Incidentally, the braking reaction time can be explained by replacing acceleration with braking and starting with deceleration in Fig. 3. Here, from the safety point of view reaction is considered to be more severe when stopping than when starting, but because of the automatic control in ACC, it is appropriate that they are both the same. Therefore using the braking reaction time in the present research is likely to evaluate on the low side (safe side).

#### 4.3.2 Analysis method

In this research, a simple model of tracking with constant headway within congestion was assumed as shown in Fig. 4. In other words, it was assumed that even with advanced ACC the headway within congestion is unchanged, the same as in (1), and only the acceleration reaction time when starting is shortened by  $\alpha$  seconds.

Also, assuming the first-in first-out condition is satisfied in congestion, it is possible to calculate the extent in which the congestion is cleared faster by the shortened acceleration reaction time using a point queue (see Fig. 5).

Looking at actual traffic phenomena in micro terms, it is possible that an ordinary car following behind a car equipped with advanced ACC could also be induced to have a shortened acceleration reaction time. However, the evaluation of traffic phenomena in micro terms is not the intention of this research, nor is there data to form its basis, so it was assumed that the acceleration reaction time was only effective on cars equipped with ACC, and that there was no effect on a following ordinary car.

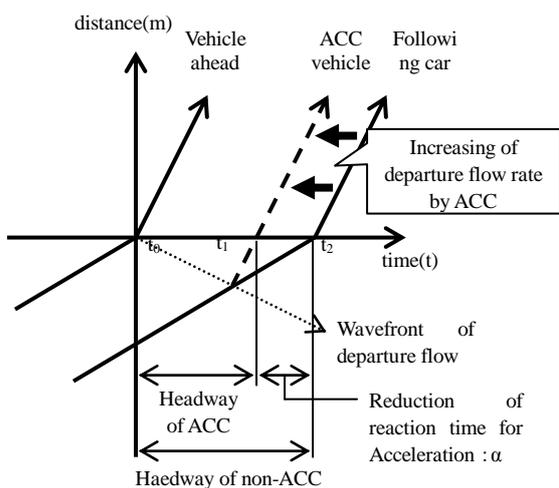


Figure 4 Time-space diagram around bottleneck

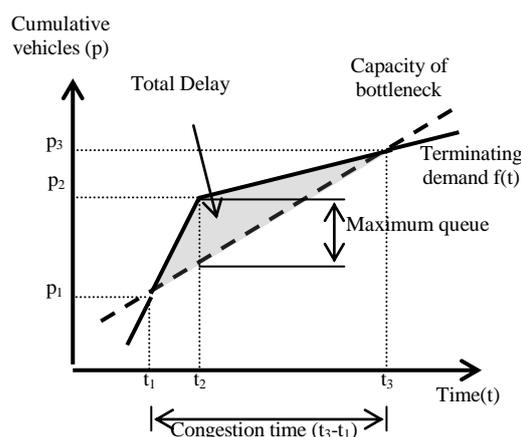


Figure 5 Queuing diagram

#### 4.3.3 Setting the terminating demand

The terminating demand was set for time bands (5 minutes) taking into account the terminating time at the bottleneck for the quantity of traffic passing a vehicle detector located immediately upstream of the tail end of congestion. In this case, the values of arrival time were

calculated for just before the occurrence of congestion and after the congestion was cleared from the data of the vehicle detector upstream of the bottleneck using the reverse time slice method taking the movement time and space into account, and the terminating demand was set based on this. Also, the difference between the number of vehicles arriving at the bottleneck obtained as described above and the cumulative number of vehicles actually passing was corrected in accordance with terminating demand for each time band. Assuming the number of vehicles passing the bottleneck is the capacity, it was confirmed that the congestion occurrence and end times were reproduced.

#### 4.3.4 Setting the capacity

If the acceleration reaction time can be shortened by  $\alpha$  seconds by advanced ACC, the starting flow rate at the front of the bottleneck for each time band when the rate of usage of advanced ACC is  $a\%$ , in other words the capacity  $q_a$  (pcu/h), is given by the following Equation (1). As the time involved in congestion becomes longer, the starting flow rate reduces, and the headway during congestion  $T_0$  takes this into account.

$$q_a = 3,600 / (T_0 - \alpha_a) \quad (1)$$

Where,

$T_0$ : Average headway for the time band during congestion (advanced ACC usage rate 0%) (sec.)

$\alpha_a$ : The acceleration reaction time shortening per vehicle including ordinary vehicles for an advanced ACC usage rate of  $a\%$  (sec.)

The passenger car equivalent of heavy vehicles was taken to be 1.5.

#### 4.3.5 Setting the location to be studied

In this research, the area near the Kobotoke Tunnel on the Chuo Expressway Tokyo-bound was selected as a representative congestion point at a sag or tunnel in Japan, and a preliminary calculation was carried out using the vehicle detector data for 2002 (see Fig. 6).

Congestion occurred in the vicinity of Kobotoke Tunnel 75 times in the 12 month period of 2002. Of this 75 times, excluding congestion caused by traffic accidents or congestion occurring at other points, in other words including only the congestion where the front was near Kobotoke Tunnel, the number of times was 43 (congestion time: average 3.25 hours, maximum congestion length: 9.2km). In this research, 5 instances of congestion of differing

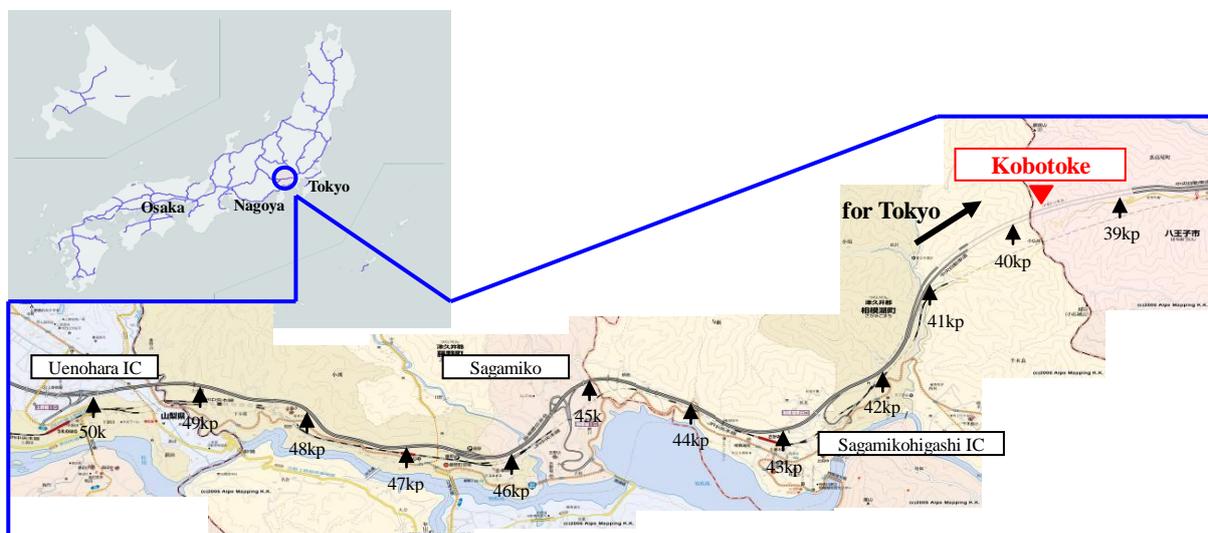


Figure 6 Study route

size were chosen from among these 43, and preliminary calculations were carried out for the effect of clearing of the congestion due to advanced ACC (see Table 2, Fig. 7).

Here congestion is defined as the state where the spot speed at the vehicle detector is continuously less than 40km/h.

Table 2 Dates and times for calculation

Congestion scale	Date	Congestion time (h)	Max. congestion length (km)	Congestion volume* (km.h)
Large ↓ Small	2002.04.14(sun)	8.0	19.9	79.6
	2002.08.09(fri)	4.7	13.0	30.4
	2002.06.30(sun)	3.3	12.1	19.7
	2002.04.07(sun)	1.1	4.7	2.5
	2002.09.14(sat)	0.5	2.0	0.5

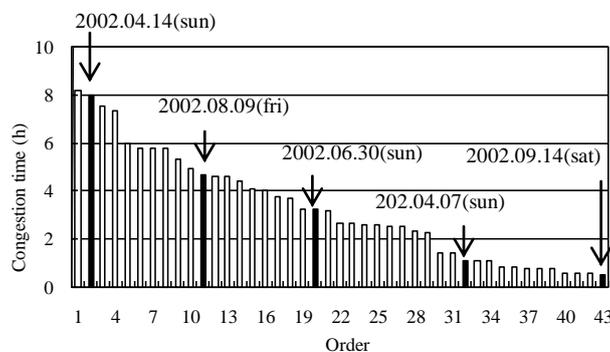


Figure 7 Congestion time

#### 4.4 Preliminary Calculation Results

Preliminary calculations were carried out for congestion time, maximum queue, and congestion loss, for each time band and for each advanced ACC usage rate (25%, 50%, 75%, and 100%), and the results are shown in Tables 3 to 5, and Figs. 8 to 11. According to these results the greater the advanced ACC usage rate the earlier the congestion is cleared.

For example, for the congestion that occurred on 14<sup>th</sup> April and extended for about 20km, it can be seen that for an advanced ACC usage rate of 25% the congestion time was shortened by about 10%, and the maximum queue and congestion loss were both reduced by about 30%.

Also, for an advanced ACC usage rate of 50%, it can be seen that the congestion time is shortened by 30%, and the maximum queue and congestion loss were both reduced by about 60%.

Incidentally, as shown in Table 8 and Fig. 11, the flow rate at this time was improved by only about 3.5 to 4% in the case of 25% advanced ACC usage rate, and by 7.5 to 8.5% in the case of 50% advanced ACC usage rate. Here, the smaller the congestion volume, the higher the traffic flow rate tends to be. This is because the terminating demand is small and the time in the queue for the congestion is not long, so the congestion is cleared before the drivers lose their desire to follow and before the starting flow rate from the front reduces significantly.

Table 3 Relationship between ACC usage rate and congestion time

Date \ ACC usage rate	Congestion time (h)				
	0%	25%	50%	75%	100%
2002.04.14(sun)	8.0	7.3	6.6	5.8	3.9
2002.08.09(fri)	4.7	3.9	3.1	2.6	2.2
2002.06.30(sun)	3.3	3.0	2.6	2.1	1.5
2002.04.07(sun)	1.1	1.0	0.8	0.5	0.3
2002.09.14(sat)	0.5	0.0	0.0	0.0	0.0

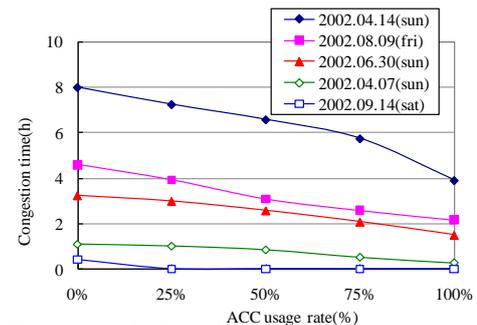


Figure 8 Relationship between ACC usage rate and congestion time

Table 4 Relationship between ACC usage rate and Maximum queue

Date \ ACC usage rate	Maximum queue (pcu)				
	0%	25%	50%	75%	100%
2002.04.14(sun)	1,737	1,199	741	387	154
2002.08.09(fri)	898	698	506	348	189
2002.06.30(sun)	699	511	319	221	121
2002.04.07(sun)	191	119	64	28	8
2002.09.14(sat)	19	0	0	0	0

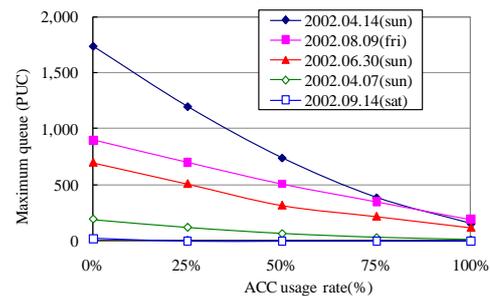


Figure 9 Relationship between ACC usage rate and maximum queue

Table 5 Relationship between ACC usage rate and congestion loss

Date \ ACC usage rate	Congestion loss (pcu.h)				
	0%	25%	50%	75%	100%
2002.04.14(sun)	8,279	5,548	3,226	1,273	255
2002.08.09(fri)	2,192	1,426	851	472	183
2002.06.30(sun)	1,405	932	517	217	49
2002.04.07(sun)	107	51	19	8	1
2002.09.14(sat)	3	0	0	0	0

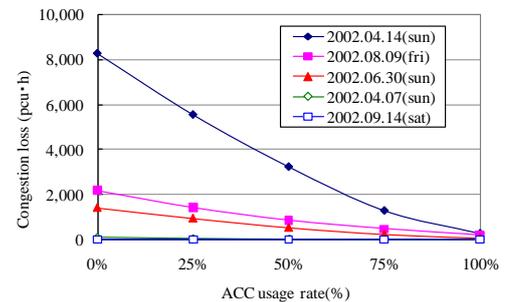


Figure 10 Relationship between ACC usage rate and congestion loss

Table 6 Relationship between ACC usage rate and traffic flow rate

Date \ ACC usage rate	traffic flow rate (pcu/h)				
	0%	25%	50%	75%	100%
2002.04.14(sun)	2,501	2,591	2,689	2,793	2,907
2002.08.09(fri)	2,498	2,588	2,685	2,790	2,903
2002.06.30(sun)	2,584	2,681	2,785	2,897	3,020
2002.04.07(sun)	2,654	2,757	2,867	2,987	3,117
2002.09.14(sat)	2,836	2,952	3,079	3,217	3,369

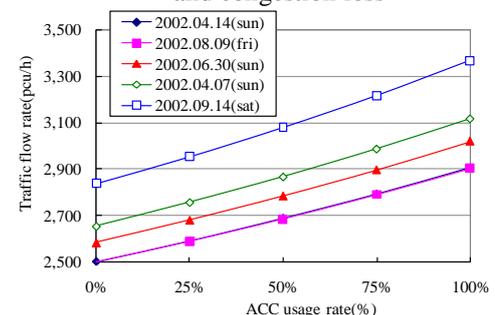


Figure 11 Relationship between ACC usage rate and traffic flow rate

Next, general equations for congestion time, maximum number of vehicles delayed, and congestion loss were prepared from the preliminary calculation data using regression analysis, assuming a constant trend between congestion scale and the magnitude of the congestion relief effect.

(1) Congestion time

$$T = 0.7939 * T_0 - 1.9800 * D_f + 0.7813 \quad (R^2=0.94) \quad (2)$$

(2) Maximum queue

$$N = N_0 * (-0.8598 * D_f + 0.8642) \quad (R^2=0.95) \quad (3)$$

(3) Congestion loss

$$L = L_0 * (-0.9256 * D_f + 0.8367) \quad (R^2=0.98) \quad (4)$$

Where,

$D_f$ : Low speed ACC usage rate (%)

$T_0$ : Current congestion time (h)

$N_0$ : Current queue (pcu)

$L_0$ : Current congestion loss (pcu.h)

Here, Fig. 12 shows the results of calculating the change in total congestion time by substitution into Equation (2) for the 43 instances of congestion with the front at the Kobotoke Tunnel on the Chuo Expressway Tokyo-bound that occurred over the 1 year period in 2002. According to Fig. 13, with a 25% advanced ACC usage rate the congestion time is reduced by about 12% (faster clearing). On the other hand, one of the assumptions in this research was that the spacing within congestion is the same regardless of whether ACC is used or not, so there is a proportional relationship between the maximum congestion length and the maximum queue. Therefore it is likely that the maximum congestion length at Kobotoke Tunnel from Fig. 10 can be reduced by about 30%. In other words, in this case there is the latent capacity to reduce the congestion volume (the area obtained by multiplying the congestion length and the congestion time, see Fig. 13) by 40%.

In contrast, in Japan an experiment with the objective of speedily clearing congestion by deploying a high visibility LED display vehicle near the current front of congestion, to attract attention by providing speed recovery information, and improve the departure flow rate by

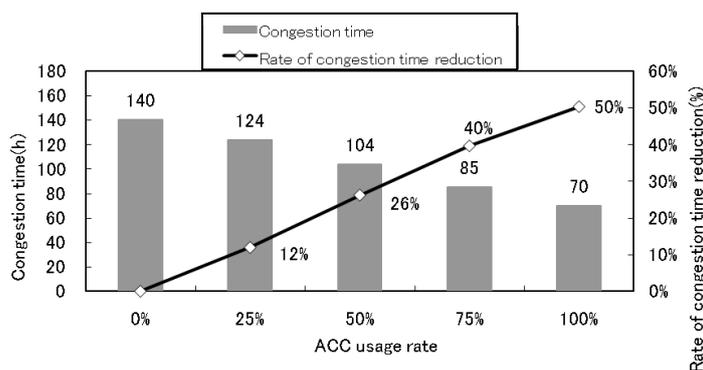


Figure 12 Effect of congestion reduction by ACC

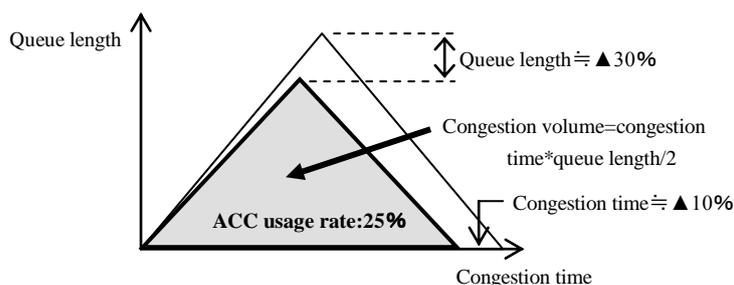


Figure 13 Image of congestion reduction by ACC

reducing the reaction delay. The specification of this experiment differs substantially from that of advanced ACC, but just looking at the assumed conditions used in this research, the specifications are not essentially different. This experiment focused on congestion whose front was at sag near the Hanazono Interchange on the Kanetsu Highway heading away from Tokyo, but it was reported that the effect, when converted into congestion volume, was a reduction of about 40%. However, it is clear that implementing a measure such as the deployment of an LED display vehicle when congestion occurs at all the main congestion locations throughout Japan is inefficient and would incur a substantial cost. Even though the locations of this research and the experiment are different, an effect equivalent to that obtained in the experiment can be obtained by a 25% advanced ACC usage rate, so in the future this may be one of the effective tools adopted.

## 5. CONCLUSIONS

This research dealt with ACC, which has evolved technically in recent years, and proposes an advanced ACC to which the function of starting and tracking is added to those of conventional ACC. Further, based on certain assumptions, the effect of early clearing of congestion was quantitatively evaluated for congestion occurring at the Kobotoke Tunnel on the Chuo Expressway Tokyo-bound, in which the sluggish forward movement behavior within congestion was corrected, and the state in which the acceleration reaction time at the front of the congestion was shortened by ACC was reproduced in micro terms.

Advanced ACC is expected to have the effect of reducing the tedium of driving with repeated starting and stopping within congestion, and the occurrence of rear-end collisions caused by distraction of attention. However, in addition it has been confirmed that it will also result in faster clearing of congestion. Of course the current specification of ACC maintains an appropriate inter-vehicle distance to suit the velocity to the vehicle in front, so it is clear that it has the effect of making congestion more difficult to occur, so when these effects are combined it is expected that congestion can be further reduced.

Automobile safety technology is making steady progress day by day, but expectations for the future improved ACC functions for making road traffic smoother are very high.

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