IMPACT EVALUATION OF A DRIVING SUPPORT SYSTEM ON TRAFFIC FLOW BY MICROSCOPIC TRAFFIC SIMULATION

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ABSTRACT

In this study, we estimated dangerous traffic situations by installing a driving support system and using a microscopic traffic simulation which was modified by adding the function of perception-response process. In this approach, a dangerous situation is assessed by detecting conflict through simulation. For this assessment, a safety indicator named TIDSS (Time Integral of Difference of Space distance and Stopping distance) was defined from the time integral of the relative distance between the leading and following vehicle when the leading vehicle brakes suddenly. This indicator is superior to existing indicators because it can evaluate any type of situation and consider the degree and duration of danger for each vehicle. The proposed approach was applied to evaluate the adaptive cruise control system (ACC) and automated platoon system (APS) for heavy trucks on the Tokyo metropolitan expressway. To evaluate the impact of ACC and APS on traffic flow, many cases with different installation rates of ACC and APS were simulated using the proposed approach, and the relation between installation rate, safety indicators, and traffic flow rate was analyzed. Thus, we found that the introduction of ACC might mitigate dangerous situations on the expressway by decreasing the traffic flow rate. In contrast, introduction of APS might mitigate dangerous situations and increase the traffic flow rate.

Keywords: Adaptive cruise control system, microscopic traffic simulation, traffic safety indicator

INTRODUCTION

A driving support system has been developed to reduce traffic accidents as well as traffic congestion. For example, the adaptive cruise control system (ACC) is one of such driving support systems, which helps to avoid rear-end collisions by maintaining the headway distance, and it has found widespread use in Japan, gradually. However, at the early stages of the ACC promotion, it was expected that a mixture of vehicles with and without ACC might trigger an increase in the number of vehicles cutting in the traffic stream and add to traffic congestion because a vehicle with ACC intends to maintain a long headway. Thus, this practice might decrease the safety and traffic flow rate. Therefore, it is necessary to evaluate the impact on traffic flow of the introduction of a driving support system. Until now, a driving support system has been evaluated in tests that used a single vehicle or simulator. However, the impact on traffic flow of the driving support system installation has not been evaluated because of the difficulty in evaluating accident occurrences with respect to the complexity of the interaction between vehicles with and without a driving support system.

Thus, this study proposes an approach to evaluate the impact of a driving support system on traffic safety and traffic flow by using a microscopic traffic simulation model that can represent the driving behavior of the individual driver/vehicle. In the proposed model, the driving behavior was represented by adding the function of the perception-response process and then detected the conflicts or near miss situations that suggest a potential accident between vehicles on the existing microscopic traffic simulation. The simulation model consisted of Paramics and the behavior of with/without the driving support system was rewritten by API. In addition, the proposed evaluation method used a traffic safety indicator, which represents conflicts instead of actual traffic accidents. This study first examined the proposed traffic safety indicators for the case of ACC in a traffic stream at a metropolitan expressway as well as the automated platoon system for heavy trucks (APS), which was also one of the driving support systems tested in Japan. Many cases with different installation rates of ACC and APS were simulated using the proposed approach and the relation between installation rate and safety indicator was assessed.

LITERATURE REVIEW

Existing Evaluation Approach

To date, a lot of driving support systems have been developed and their feasibility was evaluated through real-world field tests, and driving and microscopic traffic simulation. By using real vehicle tests, the function of the driving support system could be evaluated based on actual driving behavior in a real road network (Mizutani, 2007). However, the influence of the driving system to other vehicles in the traffic stream was not evaluated. Road environment can be simulated using a driving simulator so that the function of a driving support system can be evaluated under various traffic situations. However, the influence to other vehicles could not be evaluated even with a driving simulator (Shimizu et al. 2006). A microscopic traffic simulation might be an alternative approach to evaluate the driving support system, which makes possible the measurement of the impact on traffic flow. U.S. DOT developed the Surrogate Safety Assessment Model (SSAM), which combined existing microscopic traffic simulation and automated conflict analysis (2009). However, the vehicle behavior of the existing microscopic traffic simulation is based on uniform car behavior, and consequently traffic accidents or dangerous situations are not simulated. Because of this, the impact of any ITS installation on traffic safety cannot be evaluated by microscopic traffic simulation.

Several attempts were made to combine a driving simulator with a microscopic traffic simulator (Hasegawa, 2007). However, it has not been used widely because it requires large-scale equipment.

Evaluation of the Driving Support System

The evaluation of the ACC installation has been attempted. For instance, Fukuda et al. (2007) reported that ACC prevents speed degradation on road sag. Suzuki et al. (2004) concluded that ACC is effective in reducing travel time when the setting headway time is about 1.0 s. In contrast, Miderhoud et al. (1999) mentioned that ACC decreases the traffic flow rate when its setting headway time is longer than the actual traffic flow. Thus, the impact of ACC showed different results according to the reproducibility of the model and the parameter settings of ACC.

Several researchers have attempted to evaluate the impact of the ACC installation on traffic safety in a traffic stream. Minderhoud et al. (2001) have reported that dangerous situations increase because of the ACC installation. Nevertheless, the microscopic traffic simulation used in this study could not account for driving errors and behavior. Thus, the result may differ from a real situation. There have been fewer attempts to evaluate the impact of a driving support system on traffic flow safety conditions.

The studies of the APS impact on traffic flow are limited because the platoon system is presently in the development stage.

Thus, it is important for the proposed evaluation process of the impact of the driving support system on traffic flow to discuss the spread process and control techniques of the driving support system.

DEVELOPMENT OF THE MICROSCOPIC TRAFFIC SIMULATION MODEL

Typical vehicle behavior model

The vehicle velocity of the existing microscopic traffic simulation is based on a model of a car following the current velocity, position, and acceleration rate of the leading and following vehicles. All vehicles in the microscopic traffic simulation model are controlled in the same manner. Actually, the vehicle behavior is controlled by the perception-response process function of the driver and a traffic accident happens by errors in the perception-response process. A driving support system such as ACC contributes to traffic safety by preventing errors. Thus, this study basically modified the existing microscopic simulation model by adding the perception-response process function.

In this study, we employed Xin's model (Xin, 2008), which is based on the car following model and includes the perception-response process of the Gipps model (Gipps, 1981). The perception-response process is based on three factors, which are the visual expansion rate, the change of distance, and the instantaneous time gap. The visual expansion rate is calculated from the vehicle width, relative speed, and headway distance. The change of distance is simply the difference between the current headway distance and the headway distance at the previous scanning interval. The instantaneous time gap is derived by dividing the current headway distance by the vehicle's instantaneous speed. At each scanning interval of the driver, the following questions are checked:

1. True or False: visual expansion rate θ exceeds the threshold C_θ.

2. True or False: change of distance exceeds the threshold C_D.

3. True or False: gap time outside of $[(1-E_g)\, t_{g'}, (1+E_g)\, t_{g'}]$.
   Eg = time gap error; $t_{g'}$ = driver's desired following gap time.

If all answers are false, the vehicle cannot recognize the changing velocity of the front vehicle. Thus, the vehicle continues to either accelerate or decelerate. When none of the above checks is true, the vehicle can recognize the changing velocity of front vehicle. Then, the vehicle calculates a new acceleration following the Gipps model, which is shown in Eqs. (1-3)

$$V_{(t+t_g)} = min\left[V_n^a{}_{(t+t_g)}, V_n^b{}_{(t+t_g)}\right] \tag{1}$$

$$V_n^a{}_{(t+t_g)} = V_{n(t)} + 2.5 a_n t_g \left(1 - \frac{V_{n(t)}}{V_n^{max}}\right) \sqrt{0.025 + \frac{V_{n(t)}}{V_n^{max}}} \tag{2}$$

$$V_n^b{}_{(t+t_g)} = -t_g b_n + \sqrt{{t_g}^2 {b_n}^2 + b_n \left\{2\left(x_{n-1(t)} - x_{n(t)} - S_0\right) - t_g V_{n(t)} + {V_{n-1}}^2 / \hat{b}_{n-1}\right\}} \tag{3}$$

(3),

where

t_g:	reaction time (sec);
a_n:	maximum comfortable acceleration rate for vehicle *n* (m/s^2);
b_n:	maximum comfortable braking rate for vehicle *n* (m/s^2);
x_n, x_{n-1}:	position of vehicle *n* and *n-1*, respectively (m);
$\widehat{B}_{N-1}$:	*n*th driver's estimation for *n-1*th vehicle maximum comfortable braking rate (m/s^2);
V_n^{max}:	desired free flow speed of vehicle *n* (m/s);
S_0:	headway distance at standstill (m);

Xin's model considers the behavior of the front vehicle. However, the driver actually perceives not only the changing velocity of the front vehicle but also several of the vehicles in front. Therefore, in this study, the perception process based on the visual expansion rate and change distance is expanded to the second vehicle in front when the following conditions are satisfied. The conditions are shown in Fig. 1 and are based on the results of the research done by Suzuki (Suzuki, 2009):

1. The following vehicle is a passenger car, the first vehicle in front is a passenger car, and the second vehicle in front is a truck.

2. The following vehicle is a truck and the first vehicle in front is a passenger car.

If the following vehicle recognizes the braking of the second vehicle in front, the following vehicle will brake in advance. The chart of the simulation model for a vehicle without the driving support systems (typical vehicle) is shown in Fig. 2.

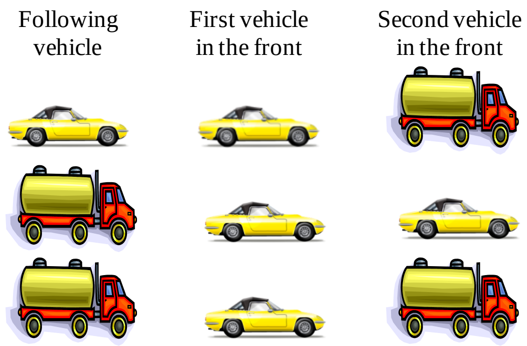

Figure 1 Condition for recognizing the second vehicle in front

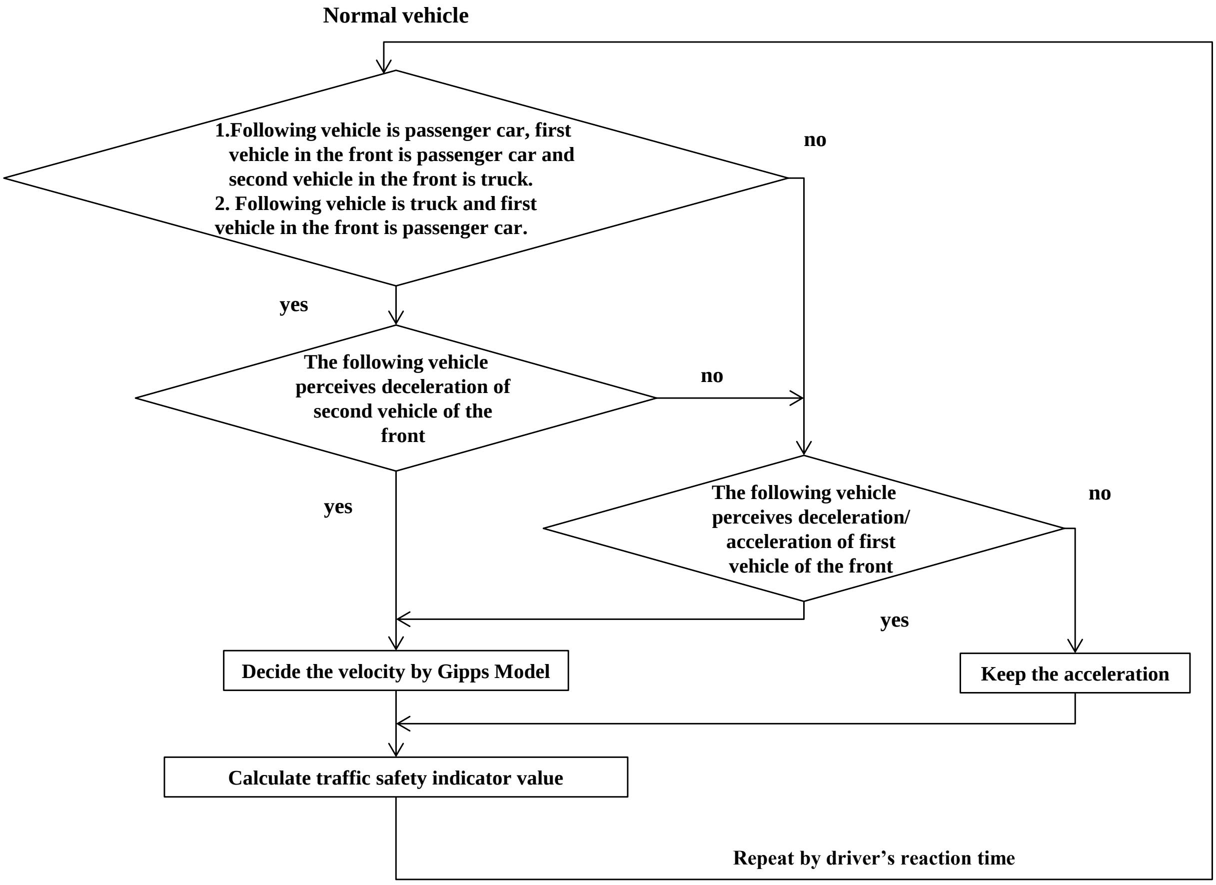

Figure 2 Flow chart of the simulation model for typical vehicle

The parameters in the proposed model were set randomly based on real following vehicle data obtained by the Japan Automobile Research Institute and the Japanese Industrial Standards:

P:	Passenger vehicle, T; Truck,
C_θ:	The threshold, normal distribution N (0.058, 0.00867),
C_D:	The threshold, normal distribution N (0.036, 0.08),
E_g:	Time gap error, normal distribution N (0.095, 0.071) sec,
$t_{g'}$:	Reaction time of ACC, 1.5 sec,

t_g: Reaction time, lognormal distribution P: N (1.08, 0.43) sec, T: N (0.92, 0.51) sec,

a: Maximum comfortable acceleration rate, normal distribution P: N (2.6, 0.57) m/s^2, T: N (2.0, 0.25) m/s^2,

b: Maximum comfortable braking rate, normal distribution P: N (3.5, 1.11) m/s^2, T: N (3.1, 0.85) m/s^2,

V^{max}: Desired free flow speed, normal distribution N (27.3, 4.42) m/s,

$\hat{b}$: Estimation maximum comfortable braking rate, P: N (3.5, 1.11) m/s^2, T: N (3.1, 0.85) m/s^2,

S_0: Headway distance at standstill, normal distribution, P: N (4.6, 1.65) m, T: N (4.5, 1.65) m,

The real following vehicle data included cruising, acceleration, deceleration, and stopping conditions. The correlation between the vehicle behavior in the simulation and a real vehicle is shown in Fig. 3.

The setting speed of the ACC vehicle follows the normal distribution N (27.3, 4.42) m/s, (maximum speed is 27.8 m/s), and the reaction time of ACC is 0.3 sec.

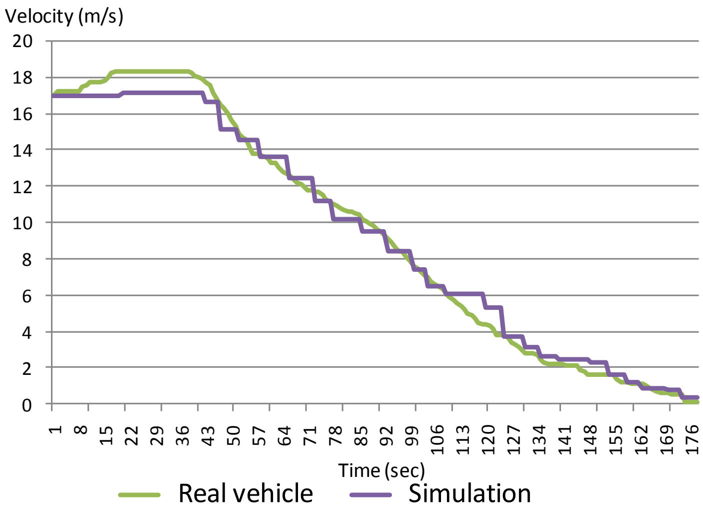

Figure 3 The vehicle behavior in the simulation and a real vehicle behavior

Behavior model of an ACC vehicle

The ACC specifications are slightly different from those preset by automobile companies. However, their fundamental functions are almost the same. The ACC fundamental functions can be explained as follows:

- Driving with constant speed if there is not a vehicle ahead.
- Maintain the headway distance at an appropriate level.
- If the speed of a front vehicle is slower than the setting speed, ACC decelerates.
- Follow a front vehicle to maintain the setting headway and adjust accordingly.
- If a front vehicle changes lanes, accelerate and continue at constant speed.

We developed an algorithm for ACC based on the above specifications shown in Fig. 4. In this study, we evaluate the high speed ACC. When the velocity of the ACC vehicle is faster than 45km/h, the vehicle will behave as an ACC vehicle and when the velocity is under

45km/h, it will behave as non-ACC vehicle. When the headway distance with the leading vehicle is less than 100 m, the ACC vehicle considers the behavior of the front vehicle constantly. In contrast, it does not consider the behavior of the second front vehicle at all conditions. The velocity of the ACC vehicle is decided by the Gipps model. The maximum acceleration and deceleration rate of the ACC vehicle is set at 2.0 m/s^2 and -2.5 m/s^2, and they are fixed by the Japanese Industrial Standards. The system reaction time is fixed at 0.3 s.

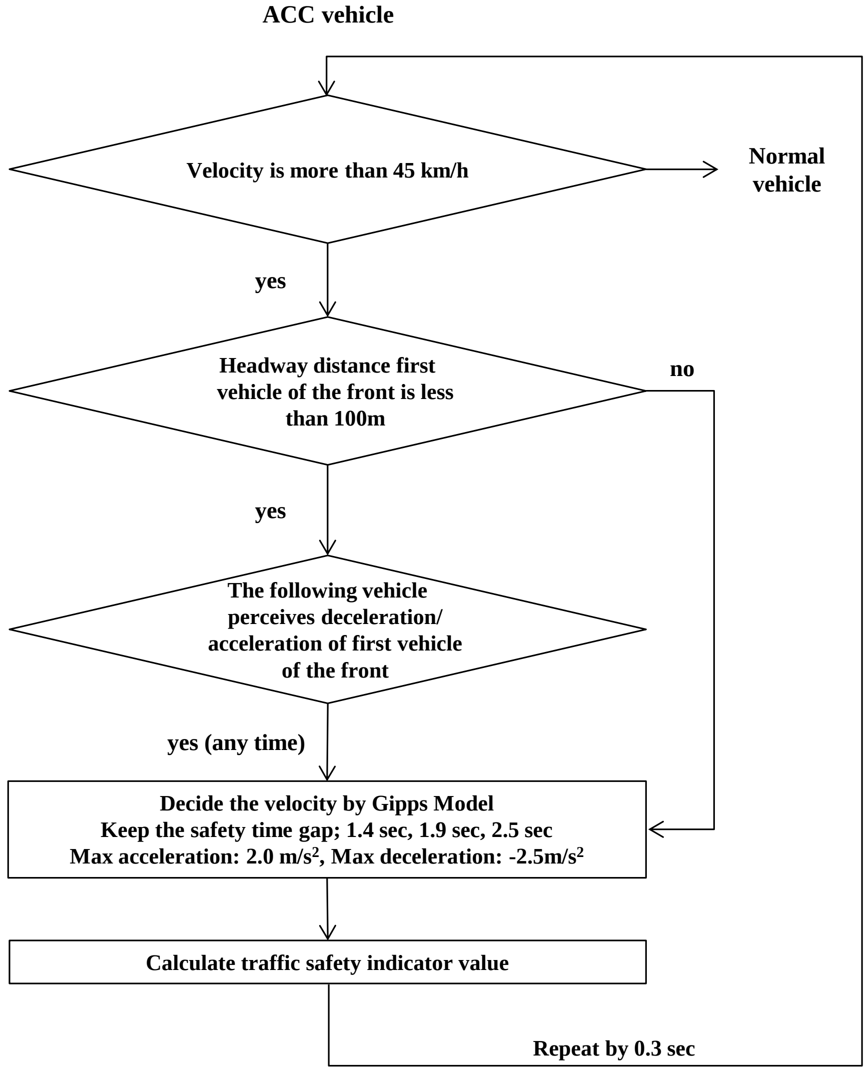

Figure 4 Flow chart of the simulation model of the ACC vehicle

Behavior model of APS

We simulated the influence of introducing APS, which is developed by NEDO (New Energy and Industrial Technology Development Organization) in Japan. This system considers three heavy trucks using a technology similar to ACC, and it is expected to increase road capacity. The lead truck had a constant velocity of 80 km/h, and the second and third truck synchronize with the lead truck and follow it. Furthermore and it is expected that all three trucks are driving as a team in one lane. The ACC model was used to simulate the behavior of the lead truck. The image of the automated platoon system of the heavy trucks is shown in Fig. 5.

Source: NEDO HP (http://www.nedo.go.jp/)

Figure 5 Automated platoon system for heavy trucks in Japan

TRAFFIC SAFETY INDICATOR

The improvement of traffic safety at an intersection, for example, is usually evaluated by comparing the number of traffic accidents before and after improving the intersection. An accident follows Heinrich's law even if it is treated probabilistically. Thus, it is not effective to estimate traffic accidents directly; instead, conflict incidents should be estimated. Several studies (e.g., Motoda, 1992) showed the correlation between a conflict incident and a revealed traffic accident. Therefore, in this study, we use a conflict incident instead of a revealed traffic accident as an indicator to evaluate the safety impact of ACC on traffic flow.

Review of the proposed traffic safety indicators

Some traffic safety indicators have been proposed to define a conflict incident. They are four types of indicators according to the definition shown in Fig. 6 and Table 1.

The indicators based on the time to collision include TTC (Hayward, 1972), TTC^{-1} (Suzuki, 2002), TTC_{2nd} (Barber, 1998), PTTC (Wakabayashi et al., 2003), TET (Minderhoud et al., 2001), and TIT (Minderhoud et al., 2001). These indicators show the remaining time before collision to the leading vehicle in the case of keeping the current velocity and acceleration rate. Above all, TTC is used for safety evaluations in several studies because it is simple and clear. Nevertheless, when the relative velocity of the leading and following vehicle is 0, these indicators cannot be calculated.

The indicators based on the relative distance of the leading and following vehicle, when the leading vehicle brakes, include DSS (Difference of Space distance and Stopping distance) (Japan Society of Traffic Engineers, 2005), PICUD (Iida et al., 2001), PSD (Allen, 1978), and MTC (Kitajima et al., 2009). PSD and MTC cannot be calculated when the velocity of the following vehicle is zero. In contrast, DSS and PICUD can be calculated in any situation.

The indicators based on the deceleration rate include ODCA (Hiraoka et al., 2008), PDCA (Hiraoka et al., 2008), DR (Deceleration rate), and a_t^2 (Noda et al., 1995). ODCA and PDCA show the deceleration rate for avoiding collision when the front vehicle brakes suddenly. a_t^2 shows the dispersion of acceleration during unit time in unit road section. These indicators are calculated by a complex formula.

KdB (Isaji et al., 2006) and PE (Suzuki et al., 2004) are classified as other indicators. KdB shows the changing rate of the square measure of the leading vehicle. PE shows the potential collision energy. KdB cannot be calculated when the relative velocity is zero. PE did not specify the threshold for which it is safe or dangerous.

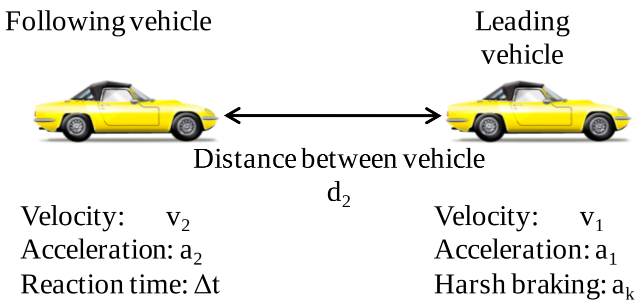

Figure 6 Definition of variable

Table 1 Traffic safety indicators

classification	Indicator	v1	v2	v2−v1	a1	a2	a1−a2	d2	ak	Δt	Other	Dangerous threshold value	v2−v1=0	a1−a2=0	v2=0
Time	TTC			○				○				Reaction time	×		
	TTC^{-1}			○				○				−0.61	0		
	TTC2nd			○			○	○				Reaction time		×	
	PTTC			○				○	○			Reaction time			
	TET			○				○				1−3 sec	×		
	TIT			○				○				1−3 sec	×		
Distance	DSS	○	○					○		○	g, μ	0m			
	PICUD	○	○					○	○	○		0m			
	PSD	○	○					○	○			1			×
	MTC	○	○					○	○			1			×
Deceleration	ODCA	○	○	○	○			○		○		sudden braking			
	PDCA	○	○	○				○	○	○		sudden braking			
	DR					○						sudden braking			
	a_t^2					○					T, a2	−			
Other	KdB			○				○				35dB	0		
	PE		○	○				○			k, t_{app}, x_{stp}, Δa	−			

Proposal of evaluation method by using traffic safety indicator

In this study, we used DSS as the traffic safety indicator. DSS is defined by the difference of the space and stopping distance as shown in Eq. (4) and Fig. 7. The space distance can be calculated by the sum of differences between the leading and following vehicle, and the braking distance of the leading vehicle. The stop distance can be calculated by the sum of the brake reaction distance and the braking distance of the following vehicle. DSS shows the freeze position of the following and leading vehicle when the leading vehicle brakes suddenly, and then the following vehicle also brakes to avoid collision. Negative DSS values mean collision because the following vehicle cannot avoid colliding with the leading vehicle when it stops suddenly. The calculation formula and dangerous threshold value are simple and clear.

$$\mathrm{DSS} = \left(\frac{v_1^{\,2}}{2\mu g} + d_2\right) - \left(V_2\Delta t + \frac{V_2^{\,2}}{2\mu g}\right), \qquad (4)$$

where

S: space distance (m);
Stop: stop distance (m);
v_1: velocity of following vehicle (m/s);
v_2: velocity of leading vehicle (m/s);
μ: friction coefficient;

g:	gravity acceleration (m/s^2);
d_2:	distance between leading vehicle and following vehicle (m);
Δt:	reaction time (sec).

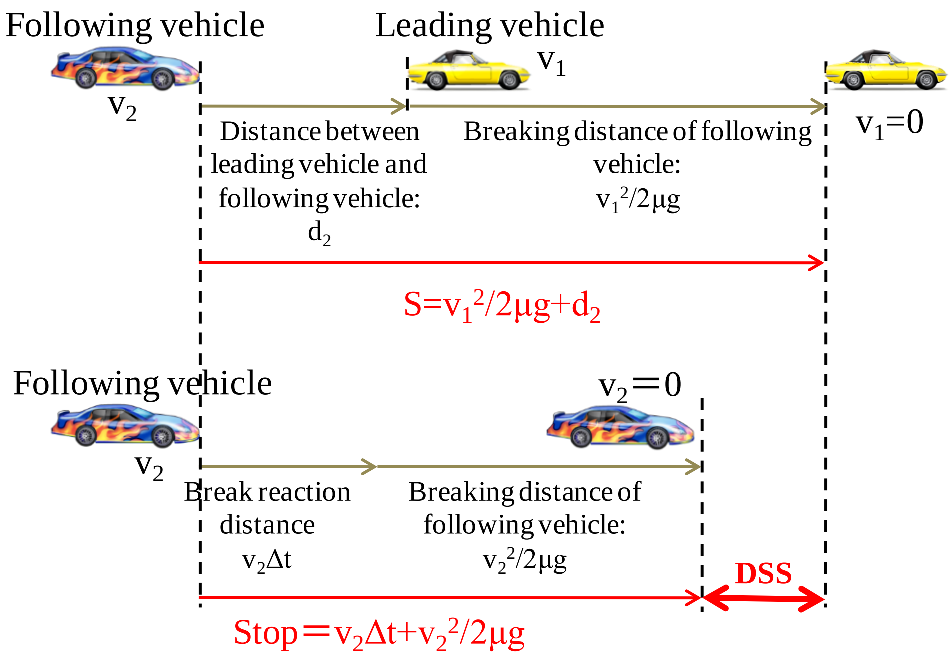

Figure 7 Definitions of DSS

Clearly, a method, which can evaluate the traffic flow safety, is needed. In the existing studies, the traffic flow safety was evaluated by the number of unsafe vehicles that were defined by the traffic safety indicator. In the case of DSS, when DSS is under 0 m, an unsafe vehicle can be defined. However, this evaluation method cannot consider the degree of danger as well as the duration. Therefore, this study proposes a new evaluation method that evaluates the safety of traffic flow by the total value of the time integrated value gap between DSS and the dangerous threshold value (Time Integrated DSS; TIDSS) as shown in Eq. (5) and Fig. 8.

$$\mathrm{TIDSS} = \int_0^t \{\mathrm{TH} - (\mathrm{DSS})\} dt \tag{5}$$

Where:
T: Time (sec);
TH: Threshold value (m);

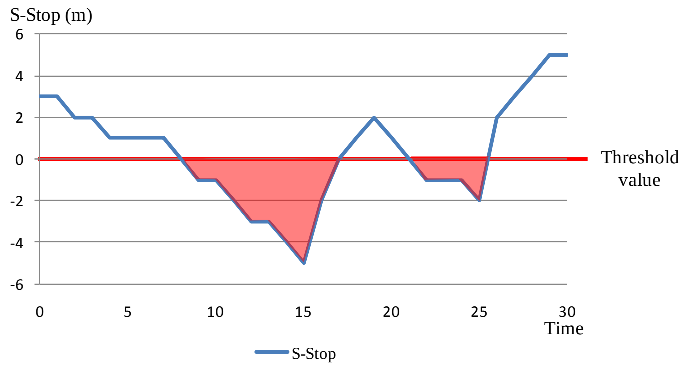

Figure 8 Example of safety evaluation by using TIDSS

This method can consider both the degree and duration of danger. In this study, the existing and the new method are observed depending on the driving support system installation rate in the traffic flow.

We compared TIDSS and traffic accidents. The simulation reproduced the traffic conditions from 9:00 to 19:30 and from 14:00 to 14:30 on Friday, November 6, 2009, and from 14:00 to 14:30 on Saturday, November 7, 2009 from Tatsumi to Kasai on the bay area (Wangan in Japanese) line of the East Tokyo Metropolitan Expressway (Fig. 9). This simulation was carried out five times. We distributed the target section between six wards and calculated TIDSS. The information on traffic accidents was offered by the Tokyo Metropolitan expressway. The target term of traffic accidents was during 2009. TIDSS correlates strongly with traffic accidents as shown in Fig. 10.

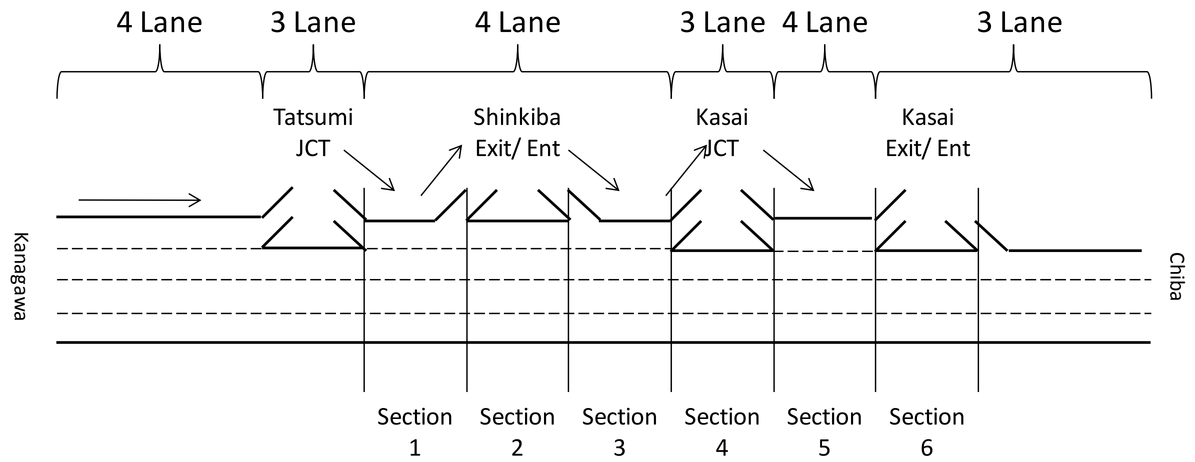

Figure 9 Outline of simulated road

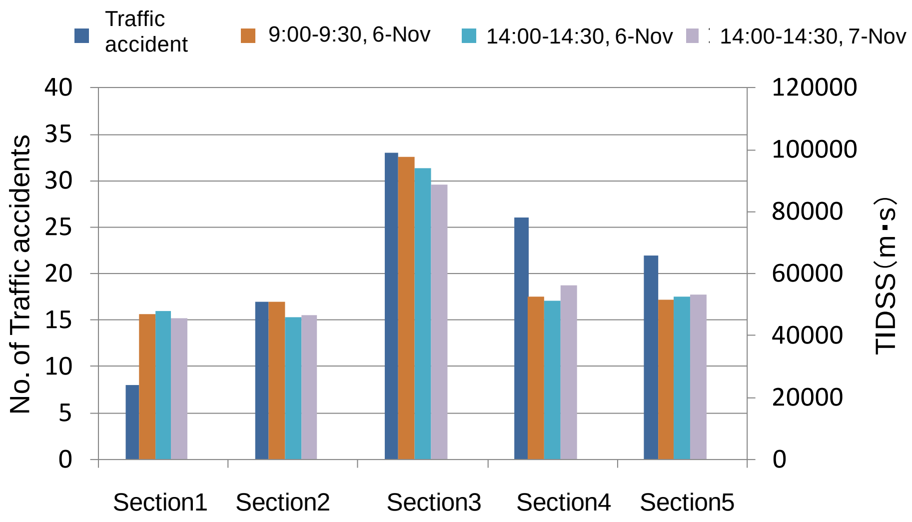

Figure 10 TIDSS and number of traffic accidents

EVALUATION OF THE DRIVING SUPPORT SYSTEM USING THE MICROSCOPIC TRAFFIC SIMULATION

To evaluate the impact on the traffic flow after the widespread use of a driving support system, we used Paramics as the microscopic traffic simulation package. A vehicle's lane changing behavior depended on the initial setting of Paramics.

Evaluation of the ACC instauration

As a case study, we developed the microscopic traffic simulation model for the section from Tatsumi to Kasai on the bay area (Wangan in Japanese) line of the Tokyo Metropolitan Expressway and simulated it under daytime conditions. We simulated 5 patterns by the ACC installation rates, which are 0%, 25%, 50%, 75%, and 100%. Each pattern was calculated five times. The truck mixture rate is 30%. The simulation time is 30 min and the time step is 0.1 s.

The velocity and traffic volume in real situations and the simulation at each point are shown in Figs. 13 and 14. From the results, it is found that the simulation reproduced the real conditions.

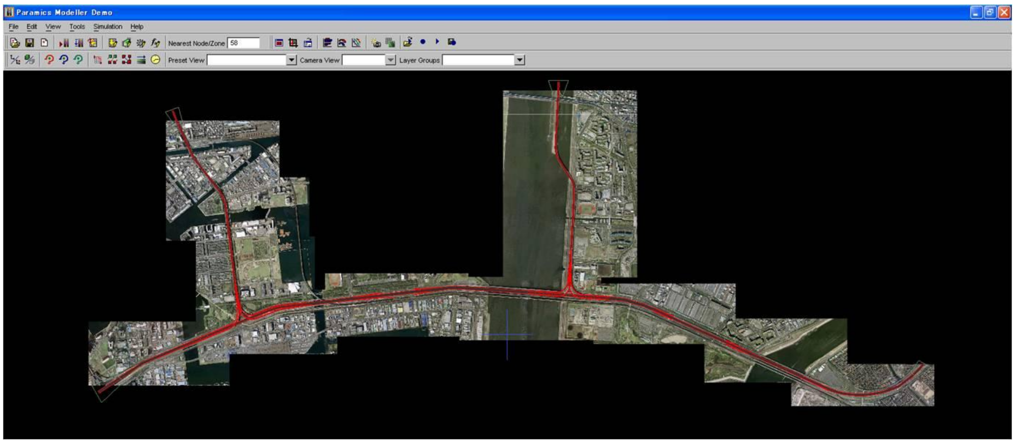
Figure 11 The simulation by Paramics

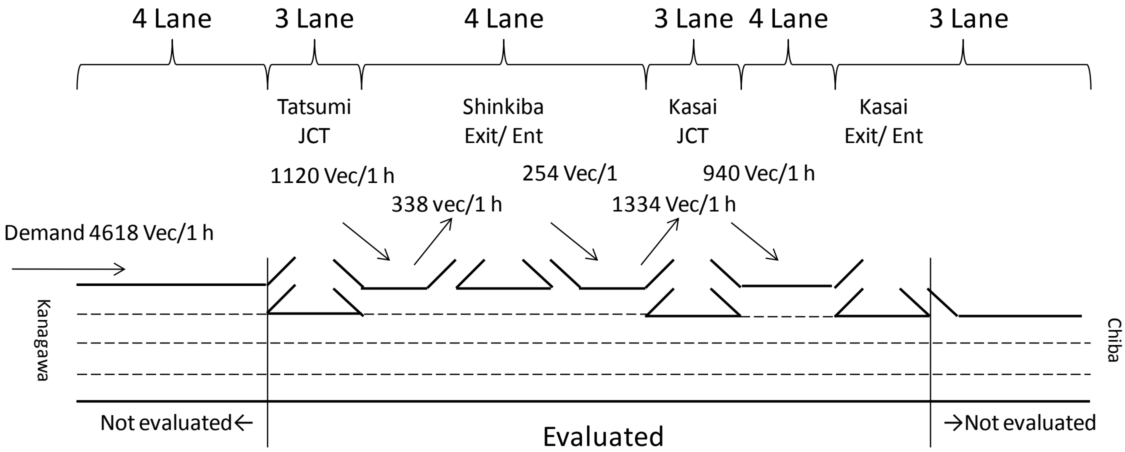

Figure 12 Outline of the simulation network

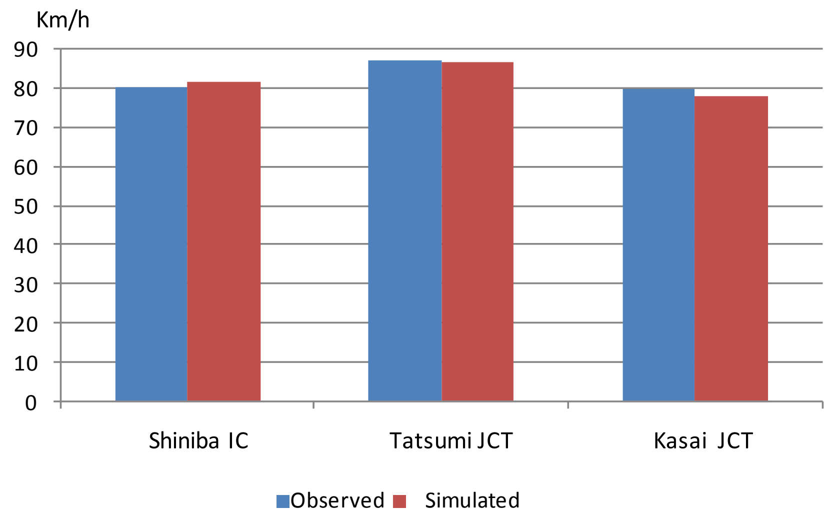

Figure 13 Velocity

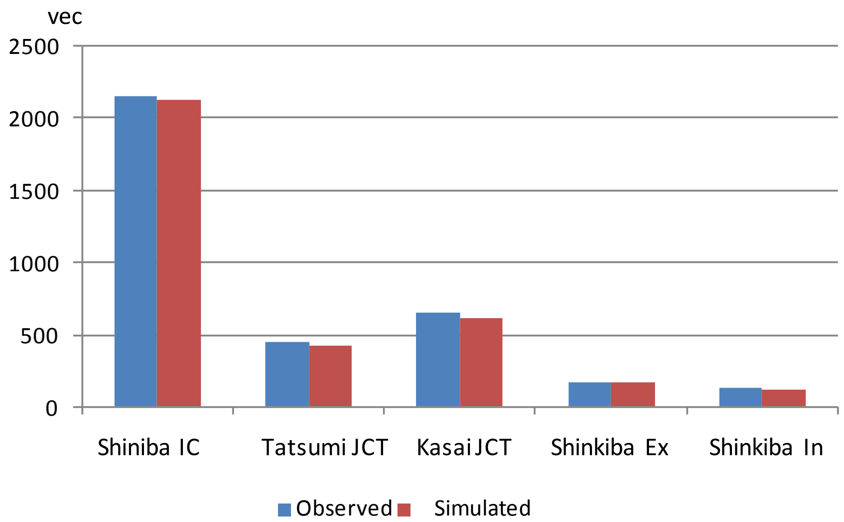

Figure 14 Traffic volume

The TIDSS and travel time of the traffic flow are shown in Figs. 15 and 16. The relation between TIDSS and travel time is shown in Fig. 17. These results are summarized as follows. The increase of the ACC vehicles contributed to traffic safety in the traffic flow. The safety of a typical vehicle and an ACC vehicle did not increase respectively by the mixing of traffic flow. An ACC vehicle also generated instantaneous dangerous situations. When the recorded data was examined, it was realized that the dangerous situations happened by cut-in vehicles. However, the duration of the dangerous situations was very short (about 0.3 s) because the ACC vehicles kept the safety headway distance. Thus, it does not seriously influence the safety of traffic flow. In contrast, the travel time increased as the ACC rate increased because the ACC maintained the safety headway distance.

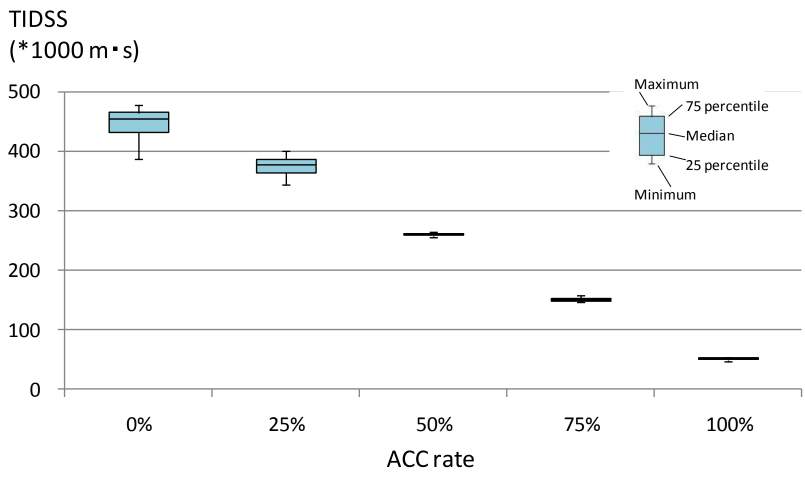

Figure 15 Evaluation result of TIDSS

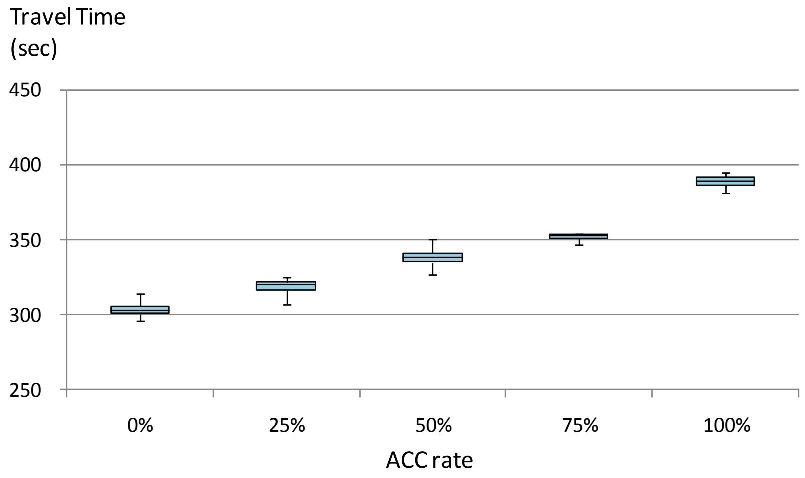

Figure 16 Evaluation result of travel time

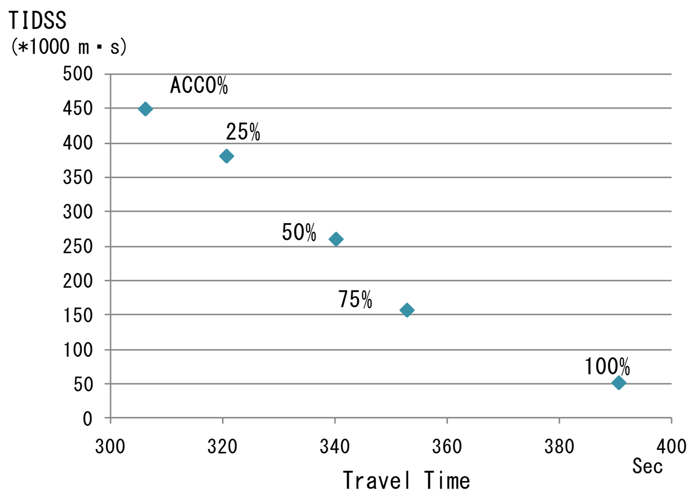

Figure 17 Relationship between TIDSS and travel time

Evaluation of APS

APS was simulated as a straight corridor such as the one depicted in Fig. 18. The traffic demand was 3000 vec/h and the truck mixture rate is 30%. 50% of the heavy trucks obeyed the platoon system.

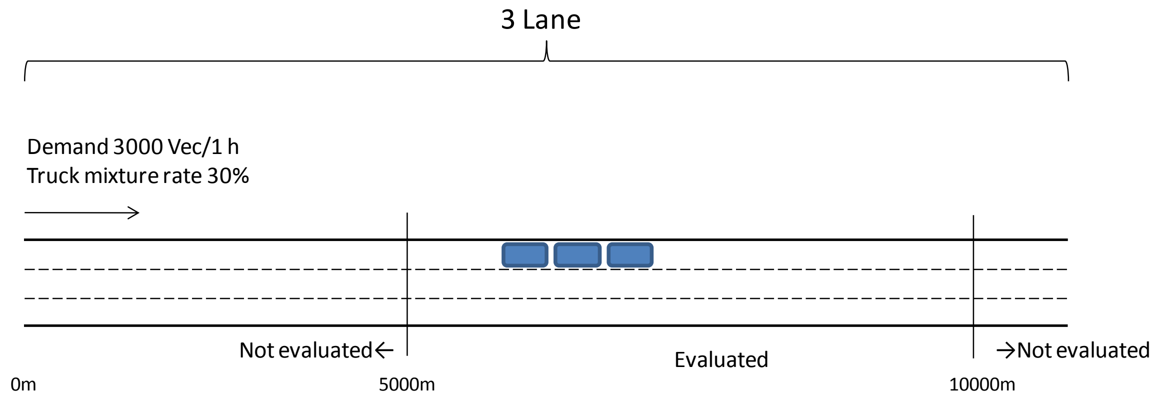

Figure 18 Outline of simulation

TIDSS and the travel time of the traffic flow are shown in Figs. 19 and 20. The relation of TIDSS and travel time is shown in Fig. 21. The results show that the platoon system contributed to traffic safety and decreased the travel time, because the heavy trucks stayed in lane and the velocity increased.

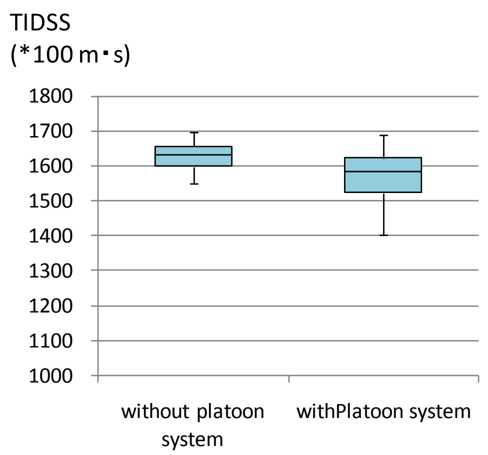

Figure 19 Evaluation result of TIDSS

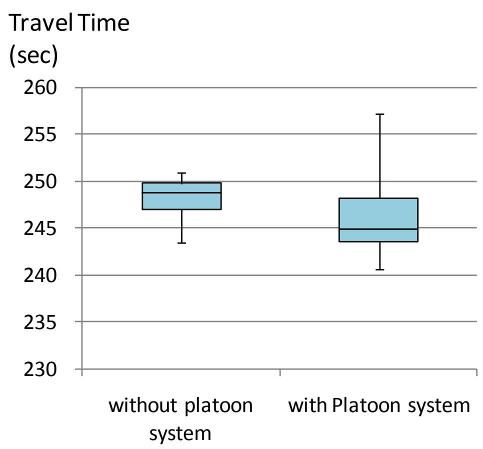

Figure 20 Evaluation result of travel time

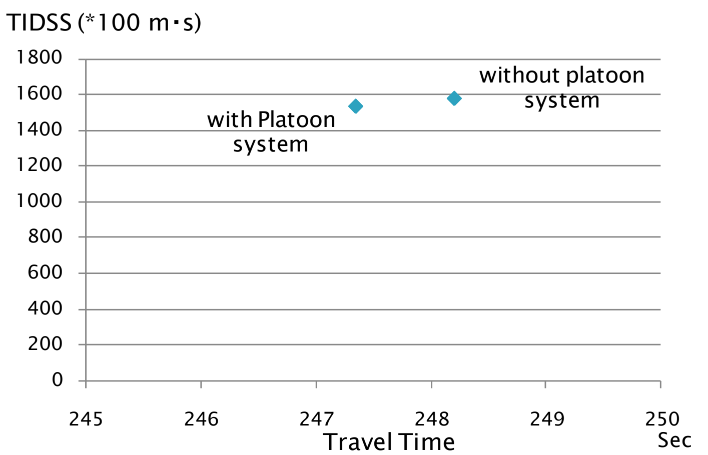

Figure 21 Relationship between TIDSS and travel time

CONCLUSIONS

We proposed an approach to evaluate the impact of a driving support system using a microscopic traffic simulation model. In this model, the perception process of the first and second front vehicle was described to simulate the driver's behavior more precisely. The microscopic simulation model consisted of Paramics, and the behavior with/without the driving support system was rewritten by API. The existing traffic safety indicators were also reviewed. The indicators were defined and classified into four types. As a result, we selected DSS as the traffic safety indicator. In addition, we proposed the evaluation indicator TIDSS by using DISS, which represents conflicts instead of actual traffic accidents. This method can consider the degree and duration of dangerous situations. Finally, many cases with different installation rates of a driving support system were simulated by using the proposed approach and the relation between installation rate and safety indicators, and travel time were analyzed. As a result of the simulation, we identified that this simulation model could evaluate the impact of the driving support system on traffic safety and flow. It was found that the ACC introduction might contribute toward the reduction of dangerous situations in the expressway and decrease the traffic flow rate. In contrast, the APS introduction might contribute toward the reduction of dangerous situations and increase of the traffic flow rate in the expressway.

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