Quantitative Performance Evaluation of Predictive Collision Warning System based on Inter-Vehicle Communication

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In this paper, the safety performance of a predictive collision warning system based on inter-vehicle communication is evaluated quantitatively by using a microscopic traffic simulator. Vehicles equipped with collision warning systems based on inter-vehicle communication exchange front-seat information with surrounding vehicles, and the systems warn the drivers if they detect any danger of collision. This paper focuses on the predictive collision warning system that can be used on multilane highways. First, the properties of the system prediction time are evaluated. Next, the properties of the diffusion ratio of the system are evaluated from the viewpoints of both the road administrators and drivers. The results show that the safety performance of the system from the viewpoint of the former increases drastically when the diffusion ratio exceeds 60%. In addition, the safety performances of vehicles equipped with the system and unequipped vehicles are evaluated quantitatively by microscopic traffic simulation from the viewpoint of the driver. A mixed scenario of equipped and unequipped vehicles is simulated. The simulation result reveals that in the case of unequipped vehicles, the average traveling distance in which no accident occurs does not depend on the diffusion ratio; in contrast, in the case of equipped vehicles, this distance is approximately 1.5–4.0 times greater.

Keywords: *inter-vehicle communication, collision warning, microscopic traffic simulation*

1. Introduction

Driving assistance systems are one of the important applications of intelligent transport systems (ITS). In these systems, a collision warning system for avoiding collision between two vehicles is expected to decrease the number of vehicle accidents. Various methods can be used to realize collision warning systems; these methods involve sensor devices [1], inter-vehicle communication (IVC) [2], or a combination of both. In particular, a collision warning system based on IVC has the potential to obtain information that cannot be obtained by a standalone system based on sensors. Such a collision warning system can be realized if vehicles are enabled with real-time positioning and seamless real-time communication. In order to assess the practical applicability of such a system and outline its future development, it is important to evaluate its safety performance.

Microscopic traffic simulation is an attractive option for evaluating the performance of the driving assistance system. The microscopic traffic simulator differs from the macroscopic one in the sense that it considers each vehicle's behavior; thus, it can obtain data for every vehicle. For the safety evaluation of the driving assistance system based on IVC, a microscopic traffic simulator was developed in ref. [3]. The safety performance evaluation of IVC by considering shadowing has also been carried out [4]. Moreover, in ref. [5], a model for road-vehicle communication was introduced in the simulator developed in ref. [3], and the safety performance was evaluated. However, this warning system assumes that the danger of a collision can be detected from the current conditions, and prediction information is not used.

In this paper, the safety performance of a predictive collision warning system in a mixed scenario of equipped and unequipped vehicles is evaluated quantitatively. In section 2, the collision warning system based on IVC is explained. The predictive collision warning system based on IVC is described in section 3. In section 4, the properties of the prediction time and diffusion ratio are evaluated using the microscopic traffic simulator. The conclusion is presented in section 5.

2. Collision warning system based on inter-vehicle communication

2.1 Inter-vehicle communication

According to ref. [6], IVC can be categorized as follows:

- Category 1 (V–V)

Communication between vehicles is carried out through direct communication between onboard equipment.

- Category 2 (V–V or V–R–V)

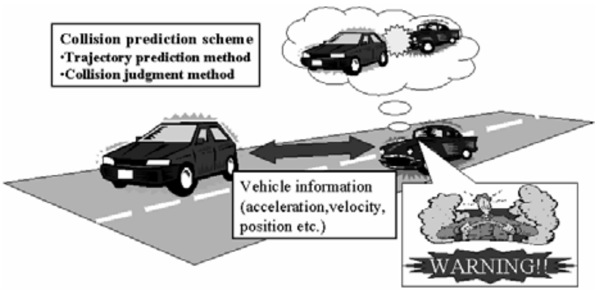

Fig.1 Overview of the predictive collision warning system.

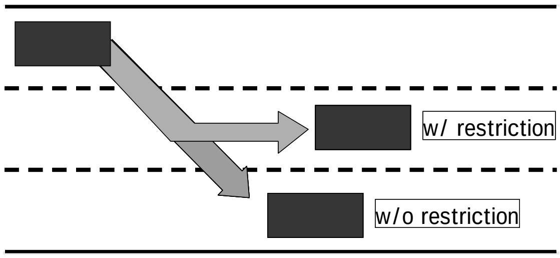

Fig.2 Restriction of movement in the lateral direction

This involves direct IVC through onboard equipment or IVC that uses radio mirror type roadside equipment.

- Category 3 (V–V, V–R–V, or V–R–R–V)

This involves direct IVC through onboard equipment or IVC via road facilities and roadside networks.

The purpose of using collision warning systems is to detect the danger of collisions and warn the driver. Therefore, either V–V or R–V can be used as long as vehicles can exchange information seamlessly in real time. In this paper, we assume that IVC in the collision warning system belongs to category 3.

2.2 Collision warning system

The collision warning system detects danger based on information acquired from the subject vehicle and surrounding vehicles, and it warns the driver accordingly. This paper considers the collision warning system based on IVC as described in ref. [7]. An overview of this system follows. Information communicated between vehicles is divided into two categories: front-seat information (pertaining to actual driving) and rear-seat information (pertaining to other information such as entertainment information).

First, the system obtains the front-seat information of both the subject vehicle and other vehicles at regular time intervals. The former is obtained from the sensor devices of the subject vehicle. The front-seat information of other vehicles within the communication range is obtained via IVC. Next, by using this information, the degree of danger is calculated; when the system judges the degree of danger to be high, it warns the driver by issuing two types of warnings—forward vehicle warning and lane change warning. When the drivers are warned, they react by braking and/or canceling their intent to change lanes.

Conventionally, studies [5] have quantitatively evaluated the safety performance of a collision warning system that determines the danger of a collision on the basis of the current conditions alone. However, the current conditions and predicted conditions have not been considered together to date.

3. Predictive collision warning system

3.1 Overview

The collision warning system of a vehicle predicts the behavior of both the subject vehicle and surrounding vehicles within a definite time period, called the system prediction time (T_p). After the front-seat information of these vehicles is obtained, the system periodically determines the degree of the danger of collision. This system predicts the relative trajectories of the surrounding vehicles based on a trajectory prediction method and estimates the likelihood of the collision based on a collision judgment method. If the degree of the danger of collision is high, the system triggers an alarm to alert the driver.

In this paper, safety performance evaluation is carried out from the viewpoints of both the trajectory prediction method and collision judgment method. These methods are described below.

3.2 Trajectory prediction method

The predicted relative trajectory is estimated linearly using the position and velocity of the vehicle. In a multilane scenario, when the system predicts the relative trajectory of a lane-changing vehicle, the predicted absolute trajectory of the subject vehicle may be beyond the driver's desired lane according to the system prediction time (see Figure 1). In this case, the system warns the driver if there are any vehicles on the lane that is adjacent to the desired lane of the driver, even if there are no vehicles on the desired lane. Such a warning may excessively suppress the lane-changing action. In order to calculate the predicted relative trajectory more realistically, we introduce a restriction on the area in which the vehicle can move laterally within the adjacent lane. Such a restriction requires the collision warning system to be aware of the lanes. First, the system recognizes the current lane on the basis of the vehicle's position and also recognizes the lane that the driver desires to move into by analyzing the vehicle's velocity

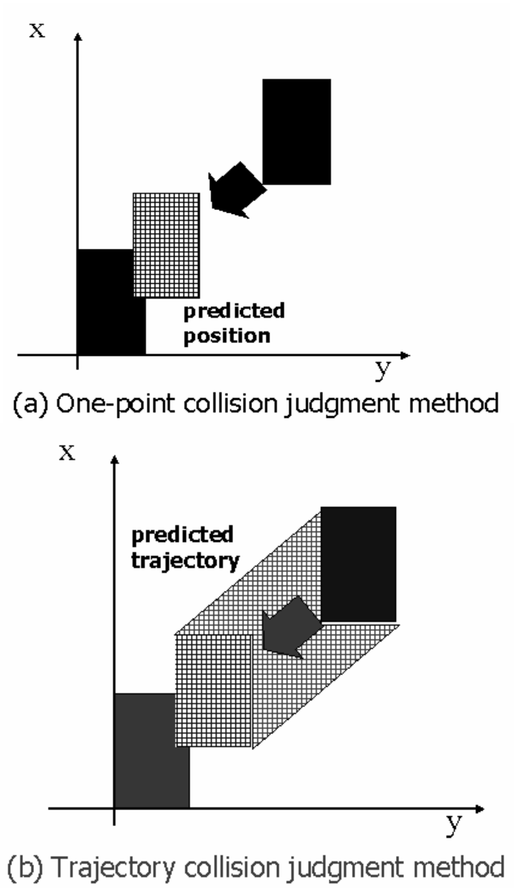

Fig. 3 Collision judgment methods.

in the lateral direction. When the driver desires to change lanes successively, the system performs the same action repeatedly.

3.3 Collision judgment methods

a) One-point collision judgment method

Figure 3 (a) illustrates the one-point collision judgment method. This method uses the relative position of each vehicle after a predetermined prediction time to estimate the possibility of a collision at the predicted position. This estimation is carried out after a duration of T_p (in seconds); the predicted relative trajectory from 0 to T_p is not calculated. However, because this method predicts only one point, the calculation load on the system is very low. If the performance of this method is close to that of the trajectory collision judgment method, the low calculation load can be considered to be an advantage.

b) Trajectory collision judgment method

Figure 3 (b) illustrates the trajectory collision judgment method. In this method, the collision warning system uses the relative trajectory to determine whether a collision would occur. Although the calculation load in the case of this method is greater than that in the case of the one-point collision judgment method, a better performance is expected because all the predicted relative trajectories (0–T_p) are used for the estimating the possibility of collision.

Table 1. Subject schemes.

		Trajectory prediction method	
		Without RL	With RL
Collision judgment method	One-point collision judgment	Scheme (A)	Scheme (B)
	Trajectory collision judgment	Scheme (C)	Scheme (D)

(RL: Restriction of the Lateral moving area)

3.4 Warning and driver reaction

The driving assistance system provides the driver with two types of warnings: forward vehicle warning and lane-change warning. The former is triggered if the system determines that the vehicle would collide with the anterior vehicle. After receiving this warning, the driver is expected to reduce the vehicle speed with a definite deceleration. However, if the driver determines that a deceleration greater than the definite deceleration is required, the driver decelerates at the required rate. In this paper, the predefined deceleration is assumed to be –0.15 G, based on ref. [6]. A lane-change warning is provided to the driver if the system determines that the vehicle will collide with any other vehicle while changing lanes. When this warning is issued, the vehicle returns to the original lane. If both the warnings are triggered, the driver reacts to them individually.

4. Performance evaluation

This section describes the quantitative evaluation of the safety performance of the predictive collision warning system by computer simulation. For this simulation, the microscopic traffic simulator including an IVC network [6] is used.

4.1 Properties of the system prediction time

To evaluate the properties of the system prediction time, four predictive collision warning schemes are compared; these are described in table 1.

4.1.1 Simulation specifications

The specifications are listed in table 2. The

Table 2. Specifications of the simulation.

Road specifications		
Lanes	3	
Road length	10 km	
Road type	Straight highway	
Vehicle density	5,15,25 veh/km/lane	
Communication specifications		
Range	100 m	
Information	Vehicle ID, position, velocity	
Communication interval	100 ms	
Vehicle specifications		
Vehicle size	Length	4.5 m
	Width	1.7 m
Driver specifications		
Total delay	Normal distribution (average = 0.7 s, standard deviation = 0.1 s) Total delay less than 0.1 s is assumed to be 0.1 s.	
Desired velocity	Normal distribution (average = 100 km/h, standard deviation = 10 km/h) If it is less than 80 km/h or more than 120 km/h, it is truncated at 80 km/h and 120 km/h, respectively.	

distribution of the total delay, as listed below the driver specifications, is based on the reaction time to the warning [7].

4.1.2 Evaluation index

We adopt the average accident interval (AAI) [5] as the evaluation index. In this paper, AAI refers to the average accident time interval for a 3-lane 10-km highway. This index can evaluate the frequency of collisions along a finite length of a road, and it is independent of road congestion.

4.1.3 Simulation results

Figure 4 shows the influence of the system prediction time on the AAI. When the prediction time is less than 2.0 s, the AAIs of scheme (A) and scheme (C) increase; when it is greater than 2.0 s, they reduce by degree. This is because it becomes difficult for the system to predict collisions when the gap between the predicted position and current position becomes large. In addition, it is shown that the restriction in the lateral direction is not

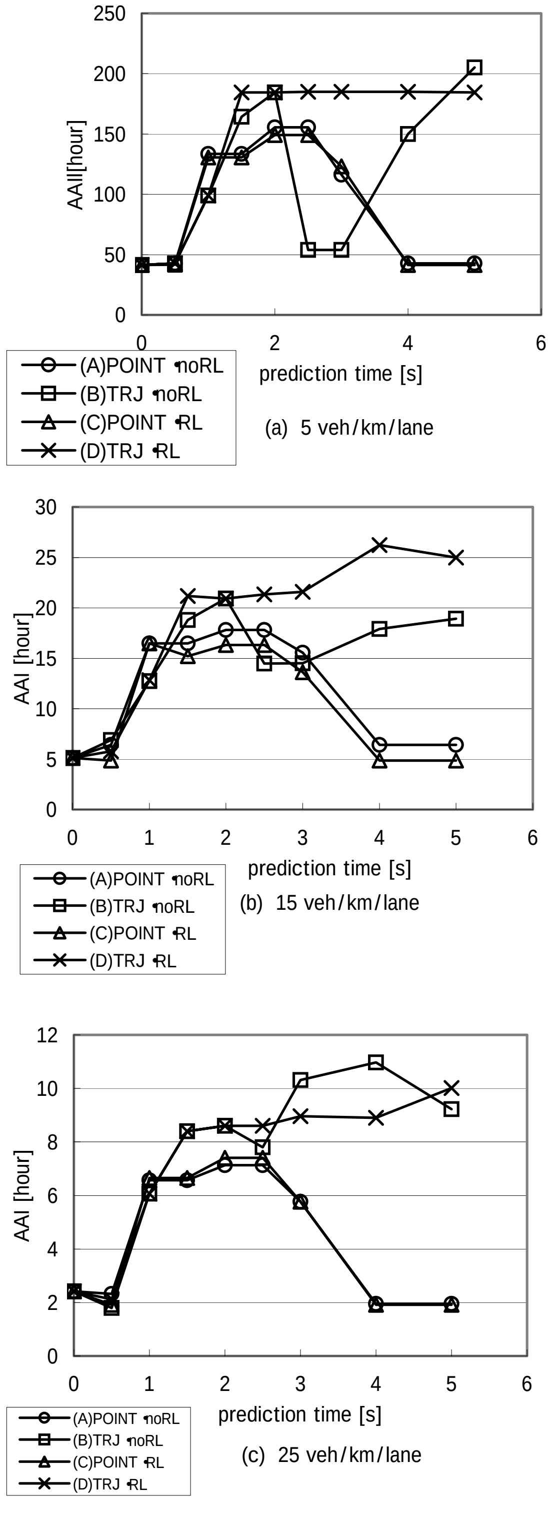

Fig 4. AAI versus system prediction time

effective in the one-point prediction method. In scheme (B), the AAI reduces to within 2.5–3.0 s of the system prediction time for the cases of 5 and 15 veh/km/lane. This result is derived by calculating the relative trajectory beyond the driver’s desired lane. Meanwhile,

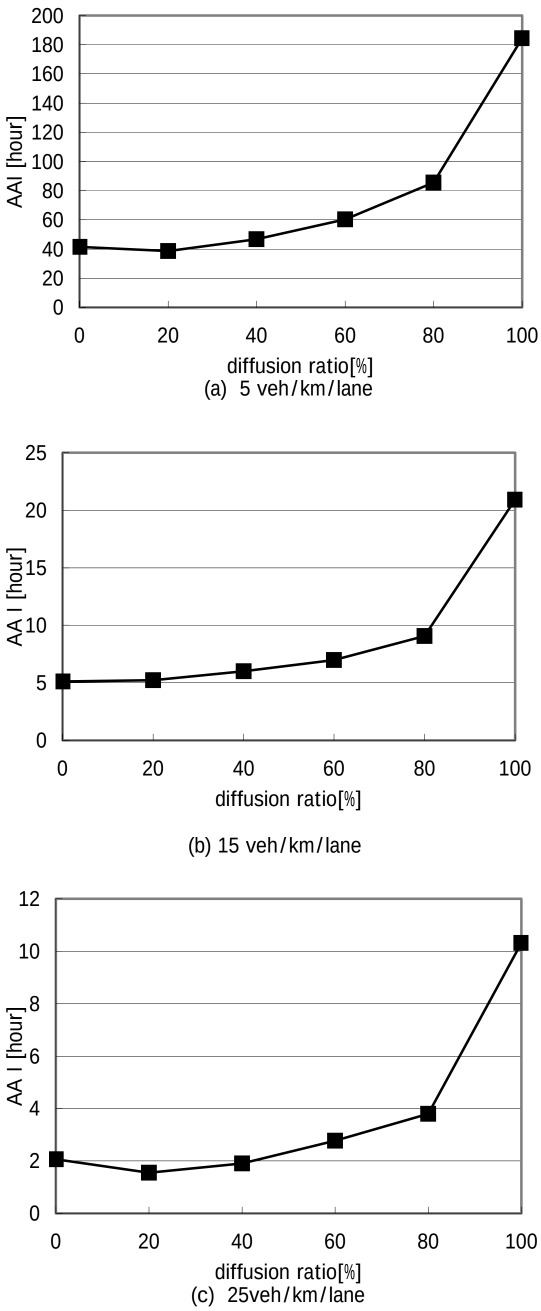

Fig. 5 AAI versus diffusion ratio.

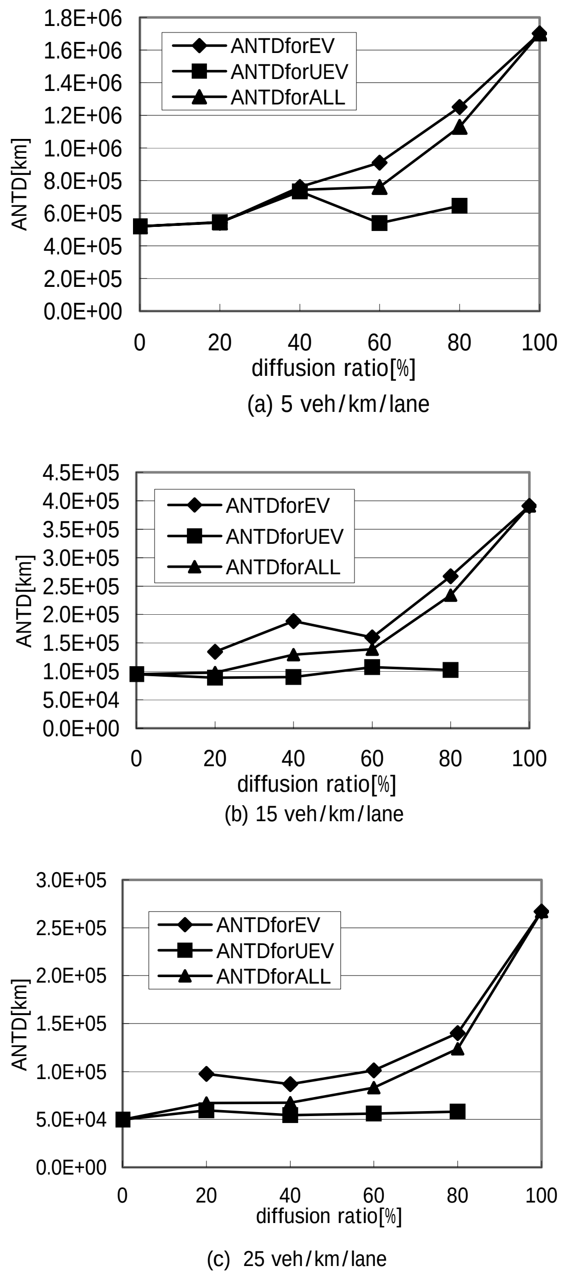

Fig 6 ANTD on the diffusion ratio

in scheme (D), in which there is a restriction in the lateral direction, such a performance degradation does not occur. This result means that the restriction in the movement along the lateral direction is effective for the trajectory collision judgment method. From the results of all the schemes, it is inferred that scheme (D) can achieve a high AAI for all prediction times. For each case of vehicle density, the maximum AAI in scheme (D) is about four times greater than the AAI in the case where the predictive collision warning system is not used. Therefore, we adopt scheme (D) as the predictive collision warning system.

4.2 Diffusion ratio properties

It is not feasible to equip all vehicles with the collision warning system; therefore, it is important to evaluate the safety performance of this system in the mixed scenario of equipped and unequipped vehicles. In this paper, the diffusion ratio is defined as the ratio of the number of vehicles equipped with the collision warning system

Table 3. Effect of the collision warning system based on communication.

Vehicle A \ Vehicle B	Equipped Vehicle	Unequipped Vehicle
Equipped Vehicle	Effective ($R_{EE} = r^2$)	Ineffective ($R_{EU} = r\,(1 - r)$)
Unequipped Vehicle	Ineffective ($R_{UE} = (1 - r)$)	Ineffective ($R_{UU} = (1 - r\,)^2$)

based on IVC to the number of all vehicles. The properties of the diffusion ratio are evaluated. There are two categories of evaluation indexes: the first is from the viewpoint of the road administrators and the second is from the viewpoint of the drivers. From the viewpoint of the former, the number of collisions on a fixed length of a highway is important. From the viewpoint of the latter, the average traveling distance of a vehicle until an accident occurs is important. In the simulation, we adopt the predictive collision warning system on the basis of scheme (D) with a system prediction time of 2.0 s. The specifications listed in table 2 are used in the simulation.

4.2.1 Evaluation indexes

The AAI is used as the evaluation index from the viewpoint of the road administrators. From the viewpoint of the drivers, we define three safety performance indexes described below (ANTD is the average traveling distance in which no accident occurs):

- ANTDforEV corresponds to equipped vehicles.
- ANTDforUEV corresponds to unequipped vehicles.
- ANTDforALL corresponds to all the vehicles.

4.2.2 Simulation results

Figure 5 plots the AAI against the system diffusion ratio. It can be seen that the AAI increases with the diffusion ratio. Moreover, it is found that the AAI increases at a significantly greater rate when the diffusion ratio is more than 60%.

Figure 6 plots the ANTD against the diffusion ratio. If the diffusion ratio is low (20% to 60%), ANTDforEV becomes approximately 1.5 times greater than ANTDforUEV. Further, it can be seen that ANTDforEV increases at a significantly greater rate when the diffusion ratio is more than 60%. Meanwhile, ANTDforUEV does not depend on the diffusion ratio. This is because the driving assistance system works only for the situation in which two vehicles that are close to each other are equipped with the safety system, as shown in table 3.

In addition, it is shown that ANTDforALL increases with the diffusion ratio.

As shown in table 3, when two vehicles (vehicle A and vehicle B) move close to each other, there are four encounter patterns according to vehicle type (equipped or unequipped). In the first pattern, vehicles A and B are equipped, and the event probability of this pattern is R_{EE}. In the second pattern, vehicle A is equipped and vehicle B is unequipped, and the event probability is R_{EU}. In the third pattern, vehicle B is equipped while vehicle A is unequipped, and the event probability is R_{UE}. In the fourth pattern, neither vehicle is equipped, and the event probability is R_{UU}. R_{EE} is proportional to the square of the diffusion ratio (r); therefore, the system is effective when $r > 0.6$.

5. Conclusion

In this paper, the safety performance of a predictive collision warning system based on IVC has been evaluated quantitatively. By using a microscopic traffic simulator, four schemes of collision prediction based on this system have been compared on the basis of the system prediction time. In particular, when the system prediction time is set to 2.0 s or greater, it is observed that the AAI in scheme (D) is about four times greater than that in the case when the system is not used. In addition, the properties of the diffusion ratio of the system have been evaluated. From the viewpoint of the road administrators, the safety performance of the system increases with the diffusion ratio; when the diffusion ratio exceeds 60%, the safety performance improves drastically. From the viewpoint of the drivers, the performances of the equipped vehicles and unequipped vehicles in a mixed scenario of these vehicles have been compared. The results of the performance evaluation show that ANTDforUEV does not depend on the diffusion ratio and ANTDforEV becomes about 1.5 times greater than ANTDforUEV for a low diffusion ratio (20% to 60%). Furthermore, ANTDforEV increases drastically when the diffusion ratio exceeds 60%.

In the future, the collision prediction algorithm should be improved, hybrid collision warning systems that involve both sensors and IVC should be investigated, and simulations considering junction areas, ramp areas, and traffic jam situations should be conducted.

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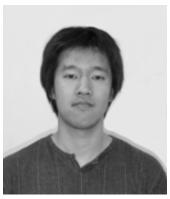

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