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Safety and Efficiency of Intersections With Mix of Connected and Non-Connected Vehicles

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ABSTRACT Connected and autonomous vehicles have been significantly studied. They are connected to a network and communicate by exchanging information with each other, so they can detect blind spots that cannot be recognized by non-connected (conventional) vehicles. Therefore, they are expected to contribute to traffic efficiency and safety. However, even if connected vehicles are put to practical use in the future, it will take time to spread to the market, so it is considered that connected vehicles and non-connected vehicles will be mixed on the road. We proposed a method of enabling connected vehicles to share the information gathered from their sensors on surrounding vehicles near intersection in the mixed situation. We then examined the safety and efficiency of passing through an intersection through simulation. We found that efficiency improved and safety could be ensured compared to using conventional methods such as stopping before the intersection without using communication and using traffic lights.

INDEX TERMS Connected vehicle, cooperative autonomous driving, V2V communication, mixed traffic.

I. INTRODUCTION

CONNECTED vehicles can exchange information with surrounding vehicles and roadside infrastructures using communication methods. Examples of these communication methods include dedicated short range communications (DSRC). DSRC is already being used in toll collection systems on expressways and in services that provide traffic information [1]. As well as such vehicle-to-infrastructure (V2I) communication, these communication technologies will be used for vehicle-to-vehicle (V2V) communication. Auto manufacturers are going to produce vehicles featuring V2V communication services for advanced safe driving support [2]. V2V communication allows connected vehicles to sense situations that cannot be recognized from only the sensor information of the vehicle. A cooperative ITS system is realized by connected vehicles and autonomous driving technology, and it is expected that the traffic will be more efficient and safer.

However, it will take time for connected vehicles to become common; thus, it is assumed that connected vehicles and non-connected (conventional) vehicles, which cannot communicate, will be mixed on the same road.

In the environment with only connected vehicles, the driving information (position, speed, etc.) of all vehicles on the road can be shared, thereby each vehicle is able to know where the other vehicles are traveling and which way they will go. That way, for example, at an intersection, each vehicle can detect in advance the presence of other vehicles approaching the intersection from the intersecting road. Then, if necessary, stop before the intersection to avoid a collision or, if there is no approaching vehicle, the vehicle can pass without stopping. Therefore, the safety and efficiency can be easily improved.

On the other hand, in the mixed situation, while it is possible to share the information between connected vehicles, it is not possible to obtain the information of non-connected vehicles. Connected vehicles cannot know where non-connected vehicles are traveling. That's why, if the approaching vehicles at the intersection are non-connected vehicles, the connected vehicle can not be able to detect the presence of them, and the improvement in safety and efficiency is incomplete. Therefore, it is necessary to develop methods that enables connected vehicles to share and use not only the information of each other but also the information of the non-connected vehicles.

We propose a method for enabling connected vehicles on a priority road to sense the presence of vehicles around them and provide that information to other connected vehicles on a non-priority road via V2V communication at an intersection where connected vehicles and non-connected vehicles are mixed. We considered safety and evaluated efficiency when connected vehicles on the non-priority road pass through the intersection.

II. RELATED WORK

A. COLLECTIVE PERCEPTION

Gunther *et al.* proposed a method for enabling connected vehicles to send EPM (Environmental Perception Messages) to inform other connected vehicles of the existence of surrounding vehicles detected by their radar sensors in addition to CAM (Cooperative Awareness Messages) [3] to notify each other of their existence in a mixed situation. It was shown that a subject connected vehicle can perceive the positions of many vehicles in a radius of 300 meters (communicable range) around even if the percentage of connected vehicles in all vehicles (penetration rate) was less than 100% [4].

We have applied similar method, in which connected vehicles on priority roads senses vehicle around an intersection and communicate that information to connected vehicles on non-priority roads.

B. EVALUATION OF SAFETY AND EFFICIENCY SIMULATION OF COOPERATIVE AUTOMATED DRIVING THROUGH INTERSECTION

Kimura *et al.* proposed a method for enabling connected vehicles on non-priority roads to obtain the speed and current position of connected vehicles on priority roads using V2V communication then determine whether to enter an intersection. As a result, the travel time of vehicles on non-priority roads decreases compared to using conventional methods such as stopping before an intersection to confirm safety without using communication and using traffic lights [5].

However, this method was performed on the premise that all vehicles were connected vehicles, so it is necessary to consider even in the presence of non-connected vehicles as well.

III. PROPOSED METHOD

A. COMMUNICATION PROCEDURE

An example of using the proposed method is shown in Figure 1, and a sequence diagram of the communication procedure is shown in Figure 2. For simplicity, some lanes are omitted.

The intersection and area in front of it on priority roads are defined as the "intersection danger range." If vehicles on the priority road are within this range, it is judged that it is dangerous for vehicles on the non-priority road to enter the

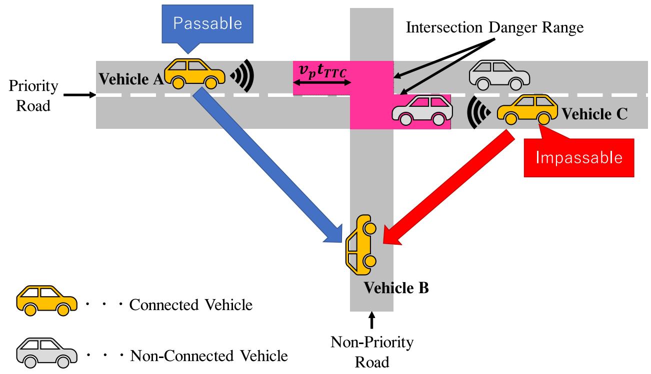

FIGURE 1. Example of using proposed method.

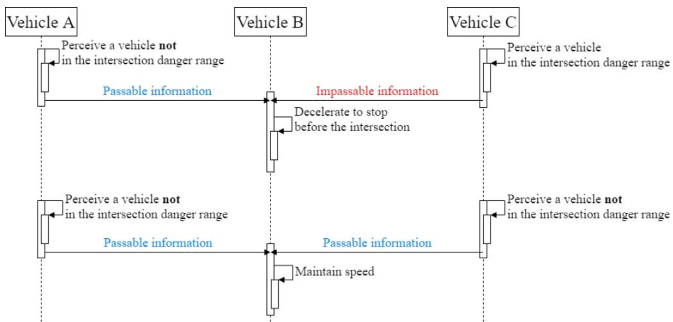

FIGURE 2. Sequence diagram of communication procedure example.

intersection. Connected vehicles on the priority road sense the intersection danger range in front or behind them using their in-vehicle sensors, then if they confirm that no vehicles exist in the range, they broadcast information (passable information) that connected vehicles on the non-priority road near the intersection can enter the intersection. If they confirm that a vehicle exist in the range, however, they broadcast information (impassable information) that connected vehicles on the non-priority road near the intersection must not enter the intersection. As illustrated in Fig. 1, the connected vehicle traveling from left to right (Vehicle A) confirms that there is no vehicle in the intersection danger range ahead and transmits passable information. The connected vehicle traveling from right to left (Vehicle C) confirms that a vehicle detected from its sensor is present in the range ahead and transmits impassable information.

A connected vehicle on the non-priority road receives information from other connected vehicles on the priority road. This information is received and updated until it enters the intersection. The connected vehicle enters the intersection without stopping before the intersection only when it receives passable information from all necessary lanes on priority roads. The necessary lanes are those intersecting the trajectory of the vehicle entering the intersection from the non-priority road. When the vehicle receives impassable information like vehicle B in Fig. 1, or when it cannot receive passable information from all necessary lanes on priority roads, it decelerates and stops before the intersection.

B. OPERATION OF A CONNECTED VEHICLE ON PRIORITY ROADS

A connected vehicle on the priority road continually performs the following operations near an intersection.

1) If the vehicle is in a position where it can sense the intersection danger range, it senses if there are other vehicles in front or behind. Otherwise, no information is sent.
2) If the vehicle ensures that there are no vehicles in the intersection danger range, it transmits passable information.
3) If the vehicle confirms that there is a vehicle in the intersection danger range, it transmits impassable information.
4) If the vehicle cannot detect the intersection danger range because of other vehicles in front or behind, no information is sent.

C. OPERATION OF A CONNECTED VEHICLE ON NON-PRIORITY ROADS

A connected vehicle on the non-priority road constantly receives information within the communicable range before the intersection and performs the following operations.

1) If the vehicle receives passable information from all necessary lanes of priority roads and does not receive any impassable information, it will enter the intersection without stopping before it.
2) If the vehicle receives impassable information from any of necessary lanes of priority roads, it decelerates and stops before the intersection.
3) If the vehicle does not receive passable information from one or more all necessary lanes of priority roads, it decelerates and stops before the intersection.

The vehicle continues receiving information from connected vehicles on the priority road after stopping. Then, if the condition 1) is satisfied, the vehicle enters the intersection.

Incidentally, non-connected vehicles on the non-priority road always stop before the intersection to check the safety of the intersection as in conventional intersections with stop signs.

D. SAFETY AND INTERSECTION DANGER RANGE

As described above, the intersection danger range is the range where vehicles on the non-priority road may collide with vehicles on the priority road when entering the intersection. Its length L is calculated using Equation (1) using the speed limit of priority roads v_p and time-to-collision (TTC) t_{TTC}.

$$L = v_p t_{TTC} \tag{1}$$

We assume that connected vehicles can be manual driving vehicles in which information is notified to the driver through on-board equipment and the driver makes decisions and performs operations, as well as autonomous vehicles. Thus we defined safety as not only to prevent collisions at intersections but also to reassure drivers of manual driving vehicles about the behavior of connected autonomous vehicles when both types are on the same road. Drivers on priority roads may be surprised by vehicles entering the intersection from non-priority roads and may brake suddenly. This may affect vehicles behind and lead to traffic jams or collisions. TTC, a criterion for determining the entering of a connected vehicle to an intersection, must consider the time margin to not surprise drivers regarding non-connected vehicles.

Therefore, TTC was set to the maximum time required for a vehicle on a non-priority road to pass through an intersection, plus the time margin to not surprise other drivers. Regarding the time margin, we referred to a study that analyzed the relationship between TTC to a pedestrian and the driver's surprise when the pedestrian suddenly started crossing the road [6]. The target was a pedestrian, but the situation seems to be similar for vehicles entering from intersecting roads.

IV. EVALUATION EXPERIMENT

A. ASSUMED CONNECTED VEHILCES

Connected vehicles in this study are assumed to satisfy the following conditions. The communication range and communication frequency were set with reference to the ITS communication requirements [7] of the Japanese Ministry of Internal Affairs and Communications, European Telecommunications Standards Institute (ETSI)'s standards [3], and Society of Automotive Engineers (SAE)'s standards [8]. The radar sensing range was set with reference to the in-vehicle millimeter wave radar [9], which has been put to practical use.

- A connected vehicle can communicate with other connected vehicles within a radius of 250 m.
- Communication frequency is 100 msec.
- A connected vehicle is equipped with a radar sensor and can detect a vehicle that is 200 m in front or behind.

B. SIMULATOR

We used Vissim [10], a microscopic multi-modal traffic flow simulator developed by Planung Transport Verkehr (PTV) AG in Karlsruhe, Germany, for the evaluation. Vissim can model various road environments according to reality and visualize traffic phenomena with 3D graphics. Figure 3 shows the simulation execution screen.

Vissim also supports the Component Object Model (COM) interface. As shown in Figure 4, Vissim can read script files by using this interface. We obtained the vehicle data on Vissim from script files programmed in Python 2, and the operation of connected vehicles was described based on those data.

C. EVALUATION ENVIRONMENT

Figure 5 shows the intersection environment we evaluated. A single intersection where two roads with a length of 1000

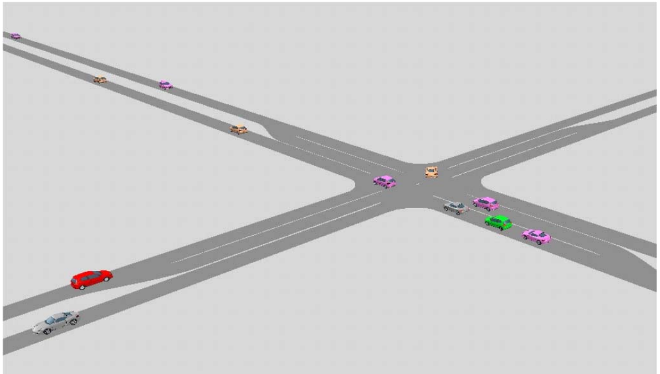

FIGURE 3. Execution screen of Vissim.

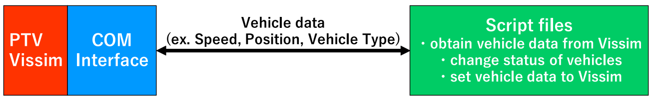

FIGURE 4. Configuration of Vissim.

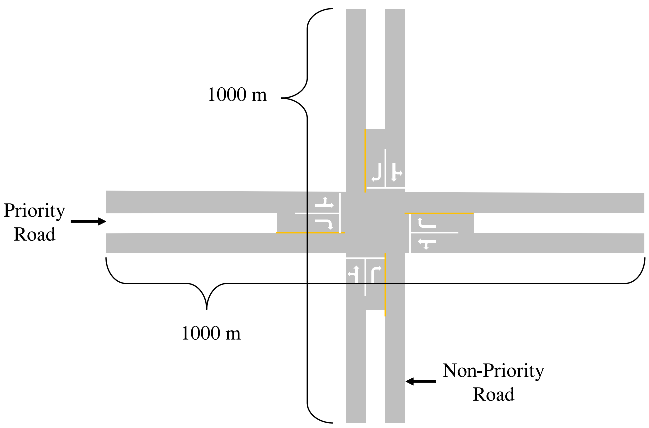

FIGURE 5. Shape of the road to be evaluated.

m long intersect at the midpoint, both have the same lane width and number of lanes, and one is designated as the priority road.

We measured the travel time and the maximum congestion length on the non-priority road as evaluation indexes of efficiency. Travel time is the average time taken for one vehicle to travel in a specific section. The measurement section was 530 m from the starting point of the road to the point where the intersection was completed.

However, because this actual travel time is affected by the length of the measurement section, we also measured the ideal travel time when passing through the same length of section without stopping and evaluated the difference between actual time and ideal time. The maximum congestion length is the maximum length of traffic that occurred before the intersection.

These evaluation indexes were evaluated by changing the number of vehicles per hour (traffic volume) and the penetration rate. Table 1 lists the parameter settings for the

TABLE 1. Simulation parameters.

Parameters	Setting
Speed limit	Priority Road: 50 km/h
	Non-Priority Road: 40 km/h
Number of vehicles in one lane per hour	50～550 vehicles per hour
Ratio of vehicles (Priority:Non-Priority)	3:1
Lane width	3.5 m
Measurement time	30 minutes
Number of measurements	10 times
Measurement section	530 m
TTC	5.0 s

simulation. The speed limit and traffic volume were set based on a Japanese road environment [11], [12]. The evaluation was conducted 10 times for 30 minutes in the simulator time, and the average was measured.

D. COMPARISON WITH CONVENTIONAL METHODS

To clarify whether the proposed method is effective, we created models of conventional methods of stopping before the intersection to confirm the safety without using communication (stop model) and using traffic lights (traffic light model). All were evaluated under the same conditions.

The stop model is the conventional intersection with stop signs. Stop signs are implemented only for the non-priority road. All vehicles on the non-priority road stop for 0.5 s at the stop sign then confirm whether there are safe gaps for vehicles to enter the intersection.

With the traffic light model, all vehicles obey the traffic lights. Figure 6 shows the traffic light settings. The cycle time, i.e., the time required for a the traffic light to cycle from green to yellow to red, was set to 120 s, and the durations of the red and green lights were determined on basis of the traffic volume ratio between the priority and non-priority roads.

V. RESULTS

A. COMPARISON REGARDING TRAVEL TIME AND MAXIMUM CONGESTION LENGTH WITH PROPOSED METHOD AND CONVENTIONAL MODELS

Figure 7 and Figure 8 show the results of travel time and maximum congestion length for each lane, respectively, for each model when the traffic volume was 500 vehicles per hour and the connected vehicles penetration rate is 70%.

Travel time shown in Figure 7 presents the difference between the actual travel time and ideal travel time for each vehicle that made a left turn, right turn or moved straight ahead. For all patterns, the travel time with the proposed

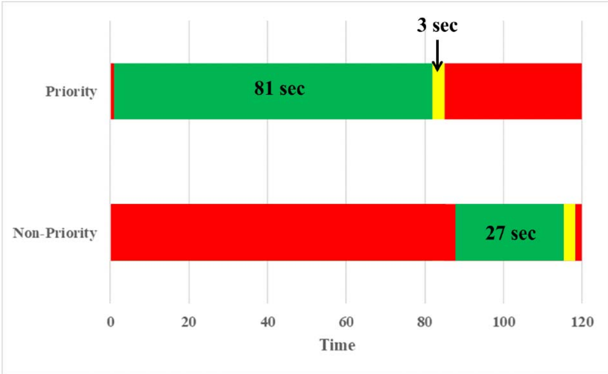

FIGURE 6. Setting of traffic lights.

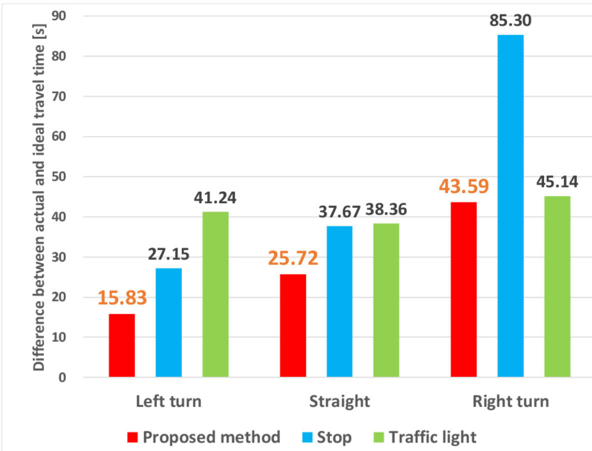

FIGURE 7. Travel time with model.

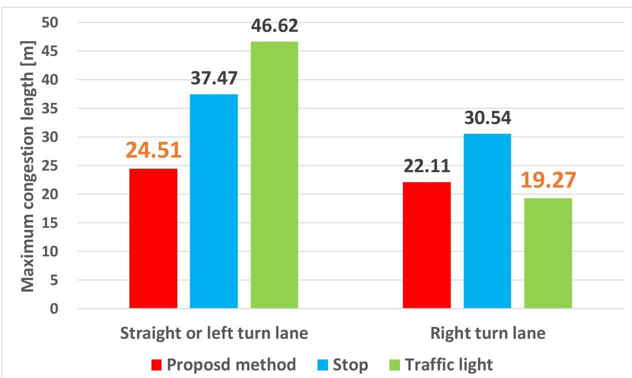

FIGURE 8. Maximum congestion length with model.

method (red) was the smallest. In particular, the left turn and straight ahead were found to have reduced travel time compared to the stop model (blue) and traffic light model (green). For the right turn, the travel time with the proposed method was half that with the stop model but did not significantly differ from that of the traffic light model.

In the straight and left turn lanes, the maximum congestion length with the proposed method was the shortest, but in the right turn lane, it was longer than with the traffic light model, as shown in Figure 8. To make a right turn with the proposed method, in addition to the information from the priority road, the information from the opposite lane is needed, so it is considered that the length is longer than that with the traffic light model.

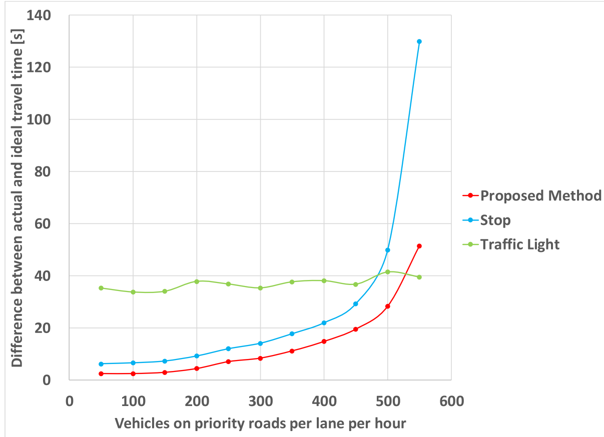

FIGURE 9. Changes in travel time with traffic volume.

B. CHANGES OF TRAVEL TIME WITH TRAFFIC VOLUME

Figure 9 shows the results of the changes in travel time when connected vehicles penetration rate was 70% and the traffic volume on the priority road was changed from 50 to 550 vehicles per hour.

The travel time with the proposed method and stop model gradually increased as the traffic volume increased while it remained almost constant with the traffic light model. When the traffic volume was 500 vehicles per hour or less, travel time with our method was the shortest. However, it was the shortest with the traffic light model when the traffic volume was 550 vehicles per hour or more.

C. CHANGES OF TRAVEL TIME WITH PENETRATION RATE

Figure 10 shows the results of travel time when the traffic volume on the priority road was 500 vehicles per hour and the penetration rate was changed every 10% from 0% to 100%. It indicates the rate of travel time reduction for each penetration rate, taking that the travel time when the penetration rate was 0% was 1.

Travel time decreased monotonously as the penetration rate increased. When the penetration rate was 50%, travel time decreased by 30% compared to when it was 0%, and about half when it was 90%.

VI. DISCUSSION

With the proposed method, travel time and maximum congestion length on non-priority roads decreased compared to stopping before the intersection to confirm safety without using communication. In addition, if traffic volume is about 500 vehicles per hour or less, our method is more

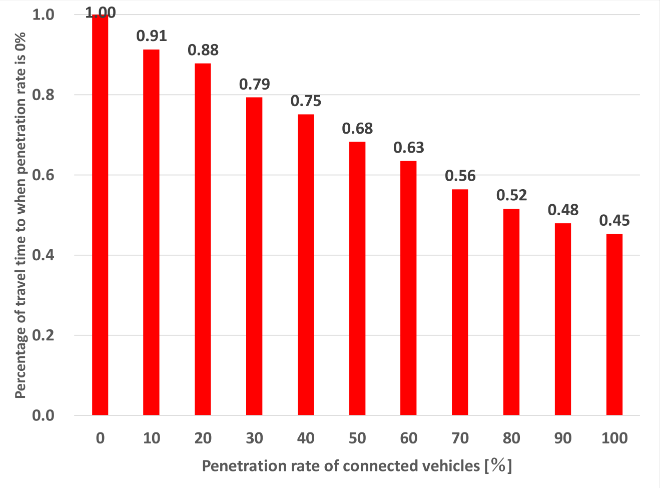

FIGURE 10. Changes in travel time with penetration rate of connected vehicles.

efficient than using traffic lights. In Japan, the average of the trafic volume is 440 vehicles per hour [12]. Therefore, the proposed method is effective at intersections of average traffic volume. Furthermore, the proposed method does not require mediation devices such as traffic lights and roadside devices because it used only V2V communication. Thus, the cost of device installation and maintenance is eliminated.

At intersections with heavy traffic such as urban areas, however, there is no room for vehicles on non-priority roads to enter, so the proposed method is not effective and traffic lights or another method are necessary.

Regarding the presence of manually driving vehicles, we found that safety was ensured by setting TTC with less surprise the driver. It is also possible to change the TTC dynamically depending on whether it is an autonomous vehicle or manually driving vehicle and other characteristics such as driver's age or vehicle type.

VII. CONCLUSION

We assumed that there will be a situation in which connected vehicles and non-connected vehicles will be mixed in the future when connected vehicles become more common. We proposed a method for enabling connected vehicles to pass through an intersection more efficiently. We conducted a simulation experiment to examine the safety and efficiency of connected vehicles on non-priority roads when passing through an intersection. We found that efficiency improved under moderate traffic volume level roads and safety could be ensured.

We believe that it is necessary to consider another method to improve efficiency even at intersections with higher traffic volume and also a protocol in other road environments than intersections that assumes a situation in which connected and non-connected vehicles are mixed.

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