Simulation Evaluation of Cooperative Intersection Traversing Method for Connected Vehicles

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***Abstract*—Connected vehicles can exchange information with each other by communicating via a network, enabling them to detect vehicles in their blind spots which cannot be seen by a vehicle alone, thereby contributing to traffic efficiency and safety. Since it will take time for such vehicles to become prevalent on roads, connected and non-connected vehicles will share the road in the future. We have developed a method that enables connected vehicles to share information gathered by their sensors on surrounding vehicles near an intersection. Simulation experiments were used to consider safety and evaluate changes in efficiency as the connected vehicle penetration rate increased. We found that safety can be ensured by adjusting the Time-To-Collision parameter dynamically, and that efficiency for an intersection with average traffic volume was improved compared with using conventional methods.**

Keywords–connected vehicle; cooperative automated 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) and Cellular Vehicle-to-Everything (C-V2X) communication. DSRC is already being used in toll collection systems on expressways and in services that provide traffic information while C-V2X is being evaluated for practical use [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 enables connected vehicles to sense situations that cannot be recognized from only the vehicle's sensor information. A cooperative Intelligent Transport System (ITS) achieved through a combination of connected vehicles and autonomous driving technology, will enable traffic to flow more efficiently and safely.

Since it will take time for connected vehicles to become prevalent on roads, we can expect connected and non-connected (conventional) vehicles, which cannot communicate with other vehicles, to share the same roads. 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

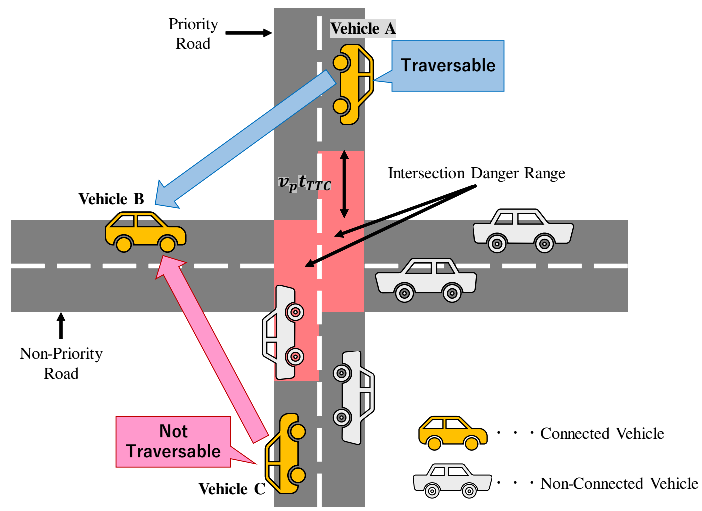

Figure 1. Usage example

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 is why, if the approaching vehicles at the intersection are non-connected vehicles, the connected vehicle cannot 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 that of the non-connected vehicles.

We proposed a method that enables connected vehicles on priority (higher traffic volume) roads near an intersection to sense the presence of nearby vehicles (both connected and non-connected) and to then share with connected vehicles on non-priority (lower traffic volume) roads via V2V communication

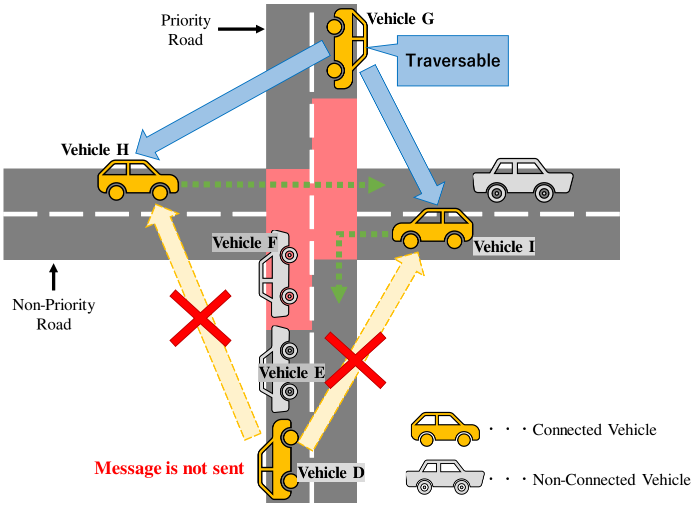

Figure 2. Example of connected vehicle unable to sense vehicles in intersection danger range

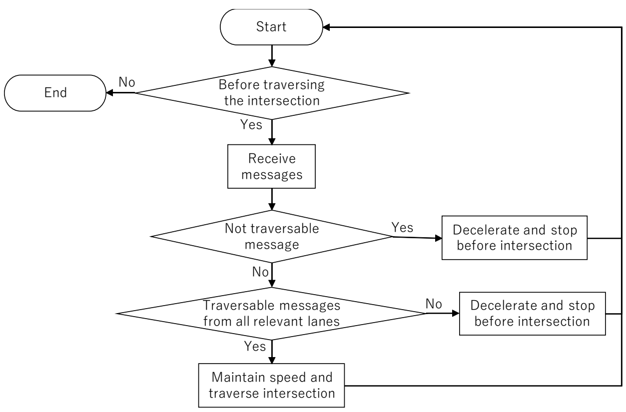

Figure 3. Judgement flow for connected vehicle on non-priority road about whether to enter intersection

information about whether they can enter and traverse the intersection. Using a traffic flow simulator, we considered safety and evaluated the relationship between traffic flow efficiency and the prevalence of connected vehicles when connected vehicles on non-priority roads approach and traverse an intersection.

The remainder of this paper is structured as follows. Section II details of related works. Section III details of the proposed method to share and use the information between connected vehicles in the mixed situation. Section IV details the evaluation of the proposed method. Section V details the results of the evaluation. Section VI details the consideration obtained from the evaluation results. Section VII details the conclusion.

II. RELATED WORK

In this section, we introduce two related works.

A. Collective Perception

Günther et al. [3] proposed a method for enabling connected vehicles to send environmental perception messages (EPM) to inform other connected vehicles of the position of surrounding vehicles detected by their radar sensors in addition to cooperative awareness messages (CAM) [4] to notify other connected vehicles of their existence in a mixed situation. It was shown that connected vehicles could perceive the positions of many vehicles within a radius of 300 meters (communicable range) around even if the percentage of connected vehicles among those vehicles (the penetration rate) was less than 100%.

B. Safety and Efficiency of Connected Vehicles Traversing an Intersection

Kimura et al. [5] proposed a method for enabling connected vehicles on a non-priority road to obtain the speed and current position of connected vehicles on a priority road using V2V communication and then use it to determine whether it is safe to enter an intersection without stopping to check for oncoming vehicles. It was shown that the travel time of vehicles on the non-priority road was lower than with two conventional methods: stopping before entering an intersection to visually check for approaching vehicles and using traffic lights.

Since this method is based on the premise that all vehicles are connected vehicles, a method is needed that takes into account the possible presence of non-connected vehicles as well.

III. PROPOSED METHOD

We first explain the communication procedure of the proposed method and then explain the operation procedure for connected vehicles. An example of using the proposed method is shown in Figure 1. For simplicity, each road has only two lanes. Here, v_p is the speed limit of the priority road, and t_{TTC} is the Time-To-Collision (TTC). These are declared in order to use for the explanation in subsection D.

A. Communication Procedure

The intersection and a portion of the lanes leading into the intersection are defined as the " intersection danger range. " If one or more 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 intersection. Connected vehicles on the priority road sense this intersection danger range (either in front or behind them). If they do not sense any vehicles in this range, they broadcast a message saying that the intersection is traversable, meaning that connected vehicles on the non-priority road approaching the intersection can safely enter the intersection without stopping to check for oncoming vehicles. If they sense one or more vehicles in this range, they broadcast a message saying that the intersection is not traversable, meaning that connected vehicles on the non-priority road approaching the intersection cannot safely enter the intersection. As illustrated in Figure 1, the connected vehicle traveling from top to bottom (Vehicle A) does not sense any vehicles in the intersection danger range ahead and transmits a " traversable message. " The connected vehicle traveling from bottom to top (Vehicle C) does sense a vehicle in the danger range and transmits a "not traversable message."

The connected vehicle on the non-priority road enters the intersection without stopping only if traversable messages are received from all relevant lanes on the priority road. The relevant lanes are those intersecting the trajectory of the vehicle entering the intersection from the non-priority road. If a not traversable message is received, like that vehicle B in Figure 1, or if a traversable message for all relevant lanes is not received, the driver decelerates and stops before the intersection.

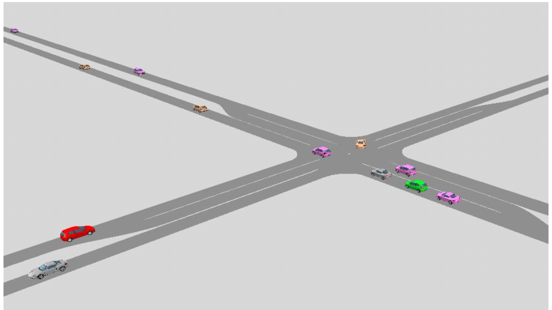

Figure 4. Execution screen of Vissim

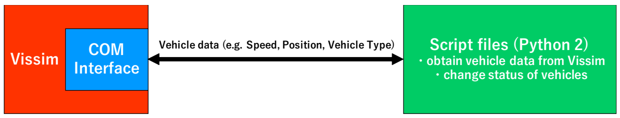

Figure 5. Configuration of Vissim

B. Operation Procedure for Connected Vehicles on Priority Road

If a connected vehicle is in a position where it can sense vehicles in the intersection danger range, either in front or behind it, it sends either a traversable or not traversable message depending on the sensed situation. Otherwise, no message is sent.

- If it does not detect any vehicles in the intersection danger range, it transmits a traversable message.
- If it detects one or more vehicles in the intersection danger range, it transmits a not traversable message.
- If the connected vehicle itself is in the intersection danger range, it transmits a not traversable message.
- If it cannot sense vehicles in the intersection danger range due to other vehicles in front or behind, no message is sent.

Figure 2 shows an example of the last situation. The connected vehicle running on the priority road from bottom to top (Vehicle D) is unable to sense vehicles in the intersection danger range (in this case vehicle F) due to the presence of a vehicle ahead of it (Vehicle E). Vehicle D thus does not transmit a message. This prevents vehicles in the intersection danger range from being overlooked.

C. Operation Procedure for Connected Vehicles on Non-Priority Road

A connected vehicle on a non-priority road approaching an intersection with a priority road constantly receives messages from connected vehicles on the priority road that are within communication range. The connected vehicle uses these messages to determine whether to enter the intersection without stopping to check for oncoming vehicles. The judgement flow is shown in Figure 3.

- If traversable messages are received from all relevant lanes on the priority road and a not traversable message is not received, the connected vehicle enters the intersection without stopping.
- Otherwise, the connected vehicle decelerates and stops before the intersection.

The situation in which a connected vehicle on a non-priority road does not receive traversable messages for all relevant lanes is illustrated in Figure 2. The connected vehicle running on the non-priority road from left to right (Vehicle H) intends to proceed straight through the intersection. A traversable message is received from vehicle G but not from vehicle D. Since the connected vehicle cannot confirm the safety of the intersection, it does not enter the intersection without stopping. On the other hand, the connected vehicle running on the non-priority road from right to left (Vehicle I) intends to turn left. Again, a traversable message is received from vehicle G but not from vehicle D. However, the connected vehicle can enter the intersection because the vehicles' trajectory passes only through vehicle G's lane.

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 with Intersection Danger Range

After defining the intersection danger range, we consider the safety of the situation. The intersection danger range is the range in which a vehicle on a non-priority road may collide with a vehicle on the priority road upon entering their intersection. Its length L is calculated using the speed limit on the priority road, v_p, and the Time-To-Collision (TTC), t_{TTC}:

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

We assume that connected vehicles can be human-operated vehicles in which information is notified to drivers through on-board equipment and drivers make decisions and perform operations, as well as autonomous vehicles. Thus, we defined safety as not only the prevention of collisions at intersections but also as the reassurance of drivers of human-operated vehicles about the behavior of autonomous vehicles when both types are on the same road. Drivers on a priority road may actually be surprised by autonomous vehicles entering an intersection from a non-priority road and brake suddenly. This may affect trailing vehicles and lead to traffic jams and collisions. The TTC, a parameter in determining whether a connected vehicle on a non-priority road enters an intersection without stopping, must include a time margin prevent surprising drivers of vehicles on the priority road.

Therefore, the minimum TTC for connected vehicles on priority roads to transmit traversable messages differ between autonomous and human-operated vehicles. While the TTC for autonomous vehicles was set to the maximum time required for a vehicle on a non-priority road to traverse an intersection, that for human-operated vehicles was set sufficiently higher to prevent drivers from being surprised. Varying the TTC enables both efficiency and safety to be achieved compared with a fixed TTC. We obtained the time margin from a study that analyzed the relationship between the TTC for a pedestrian and the driver's surprise when a pedestrian suddenly started crossing the road [6]. Although the target was a pedestrian, the situation is similar to that of vehicles entering from intersecting roads.

IV. EVALUATION

In this section, we explain the simulation environment and the way to evaluate efficiency of our proposed method.

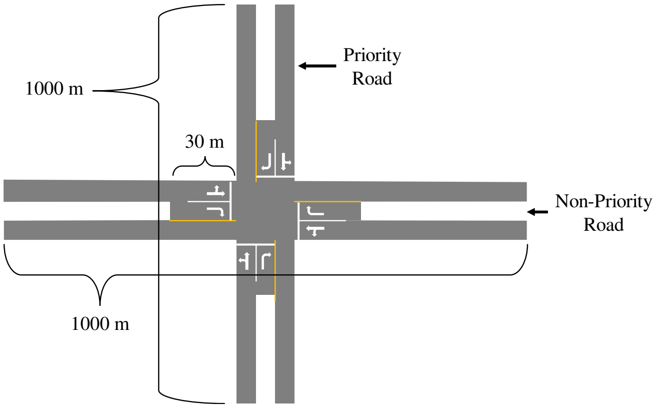

Figure 6. Layout of intersection used for evaluation simulation

TABLE I. SIMULATION PARAMETERS

Parameter	Setting
Speed limit	Priority Road: 50 km/h
	Non-Priority Road: 40 km/h
Number of vehicles per lane per hour	50 - 550
Penetration rate of connected vehicles	0 % - 100 %
Ratio of vehicles (Priority:Non-Priority)	3:1
Lane width	3.5 m
Measurement time	30 minutes
Number of measurements	10
Measurement section	530 m
Minimum TTC to transmit traversable message	Autonomous: 3.5 s
	Human-operated: 5.0 s (3.5 s + 1.5 s time margin)

A. Connected Vehicles

The connected vehicles in our simulation evaluation were assumed to satisfy the following conditions. The communication range and communication frequency were in accordance with the ITS communication requirements of the Japanese Ministry of Internal Affairs and Communications [7], the European Telecommunications Standards Institute standards [4], and the Society of Automotive Engineers standards [8]. The radar sensing range matched that of the in-vehicle mm-wave radar now in practical use [9].

- Each connected vehicle can communicate with other connected vehicles within a radius of 250 m.
- The communication frequency is 100 ms.
- The connected vehicles are equipped with a radar sensor that can detect a vehicle 200 m in front or behind.

B. Simulator

We used Vissim [10], a microscopic multi-modal traffic flow simulator developed by Planung Transport Verkehr AG in Karlsruhe, Germany. As shown in Figure 4, Vissim can model various realistic road environments and visualize traffic phenomena with 3D graphics.

Vissim also supports the Component Object Model interface, and, as shown in Figure 5, can read script files by using this interface. The vehicle data in Vissim was obtained using script files programmed in Python 2, and the operation of the connected vehicles was described on the basis of that data.

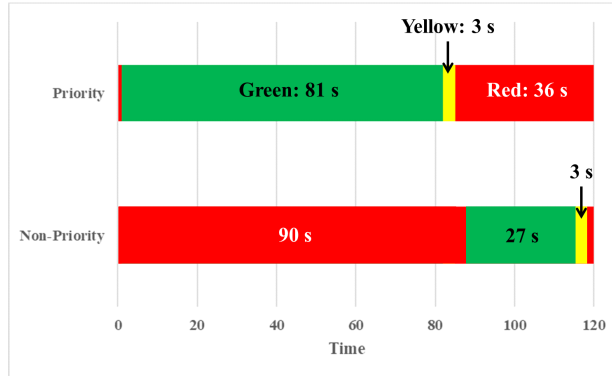

Figure 7. Setting of traffic lights

C. Evaluation Setting

The simulated environment (Figure 6) was a single intersection between two roads, each with a length of 1000 m, that intersect at the midpoint of each. The roads have the same lane width and number of lanes; one was designated as the priority road.

We measured the travel time delay (TTD) and the maximum queue length (MQL) on the non-priority road and used them as evaluation indexes of efficiency. Travel time is the average time taken for a vehicle to traverse a specific section. We set the measurement section length to 530 m, which is the length from the starting point of the road to the point where the intersection ended. Since the actual travel time depends on the length of the measurement section, we also measured the ideal travel time, i.e., the time it takes to traverse the same length without stopping when entering an intersection. We defined the difference between the actual time and the ideal time as the TTD. The MQL is the maximum length of the traffic queue at the intersection.

These indexes were evaluated by changing the number of vehicles per lane per hour (traffic volume) and the penetration rate of connected vehicles. Table I lists the parameter settings. The speed limit and traffic volume were set in accordance with the typical conditions for roads in Japan [11] [12]. The simulation runtime was 30 minutes, and there were ten runs. The results for runs were averaged.

D. Comparison with Conventional Methods

For comparison purposes, we created models of two conventional methods: stopping before entering an intersection to visually check for approaching vehicles (stop model) and using traffic lights (traffic light model). They were evaluated under the same conditions.

The stop model is the conventional intersection with stop signs. All vehicles on the non-priority road stop before the stop sign for 0.5 s and then enter it after determining that it is safe to do so.

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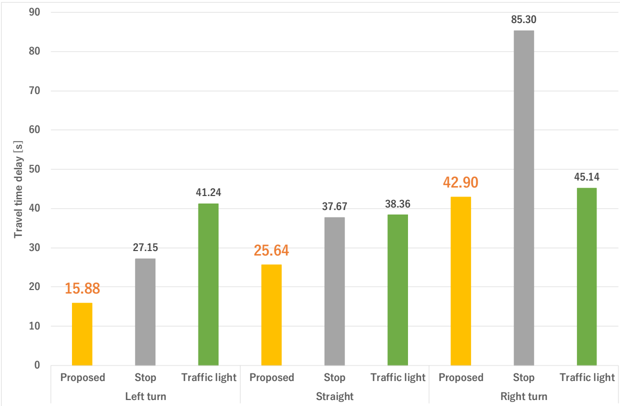

Figure 8. Comparison of travel time delay with model

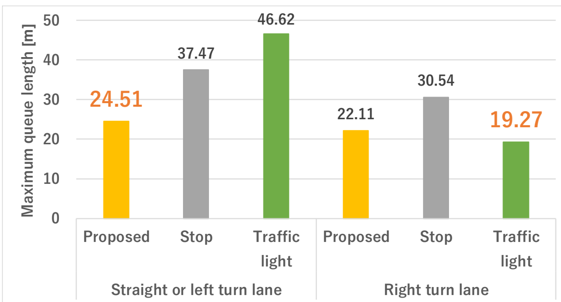

Figure 9. Comparison of maximum queue length with model

The traffic light model is the conventional intersection with traffic lights. All vehicles obey the traffic lights. Figure 7 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

We show the results of the above simulation experiment.

A. Comparison of TTD and MQL Between Proposed Method and Conventional Models

Figures 8 and 9 respectively show the results for TTD and MQL when the traffic volume was 500 vehicles per hour and the penetration rate of connected vehicles was 70%.

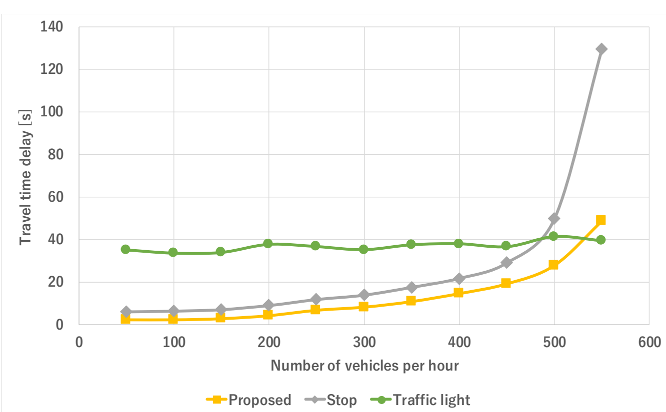

Figure 10. Changes in travel time delay with traffic volume

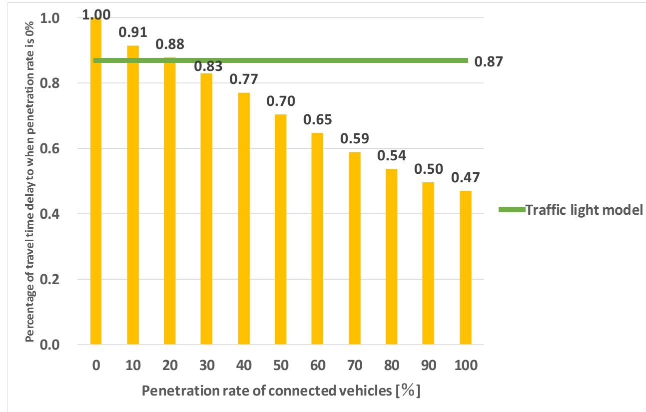

Figure 11. Decreasing rate in travel time delay against penetration rate of connected vehicles

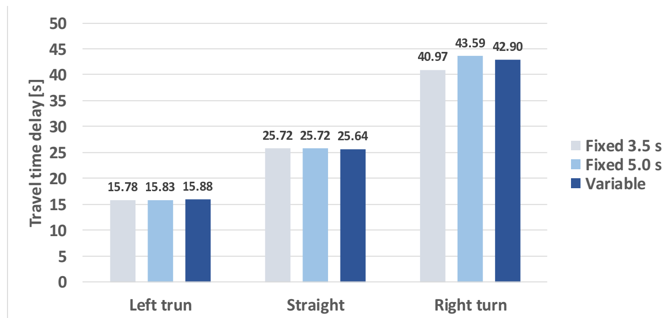

Figure 12. Changes in travel time delay with TTC

The TTD in Figure 8 represents the difference between the actual travel time and ideal travel time for each vehicle that made a left turn, right turn, or proceeded straight ahead. For all turning patterns, the travel time with the proposed method (yellow) was the shortest. In particular, the TTD for left turn and straight ahead were reduced compared with the stop model (gray) and traffic light model (green). For right turn, the travel time with the proposed method was half that with the stop model and not significantly different from that with the traffic light model.

For the straight and left turn lanes, the MQL with the proposed method was the shortest, whereas for the right turn lane, it was longer than with the traffic light model, as shown in Figure 9. To make a right turn with the proposed method, messages from connected vehicles in both lanes of the priority road and the opposite lane of the non-priority road are needed, which is assumed to have made the queue longer than that with the traffic light model. (Note that traffic in Japan runs on the left, so making a right turn requires crossing the opposite lane.)

B. Change in TTD with Traffic Volume

Figure 10 shows the changes in average TTD for all turning patterns when the penetration rate was 70% and the traffic volume on the priority road was increased from 50 to 550 vehicles per hour in steps of 50.

The TTD 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, the TTD with our method was the shortest. When the traffic volume was 550 vehicles per hour or more, it was the shortest with

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the traffic light model.

C. Decrease in TTD with Penetration Rate

Figure 11 shows the results of TTD when the traffic volume on the priority road was 500 vehicles per hour and the penetration rate of connected vehicles was increased from 0% to 100% in steps of 10%. It shows the TTD for each penetration rate, as a percentage of the TTD when the penetration rate was 0% (equal to the value of the stop model). The green line shows the result with the traffic light model under the same conditions.

The TTD decreased monotonically as the penetration rate increased. When the penetration rate was 50%, the TTD was 30% lower than when the rate was 0%, and when the rate was 90%, it was 50% lower. The TTD was less than that with the traffic light model when the penetration rate of 30% or more.

D. Comparison of TTD with Fixed Versus Variable TTC

Figure 12 shows the TTD when the traffic volume was 500 vehicles per hour, the penetration rate of connected vehicles was 70%, and the minimum TTC for connected vehicles on the priority road to transmit traversable message was one of three patterns. The first pattern was taken from the proposed method: set the TTC to 3.5 s if the connected vehicle is an autonomous driving vehicle and set it to 5.0 s if it is human-operated vehicle (variable TTC). The second pattern is to set it to 3.5 s for all vehicles (fixed 3.5 s TTC), and the third is to set it to 5.0s for all vehicles (fixed 5.0 s TTC).

The differences in the TTD among the three patterns were small for left turn and straight ahead. For right turn, the delay with variable TTC was more than that with fixed 3.5 s TTC, and less than that with fixed 5.0 s TTC. As described above, fixed 3.5 s TTC would not be safe in a situation with a mixture of autonomous and human-operated vehicles. In short, variable TTC is more efficient than fixed 5.0 s TTC and safer than fixed 3.5 s TTC.

VI. DISCUSSION

We summarize our discussion according to the results of Section V.

A. Advantages of Proposed Method

With the proposed method, TTD and MQL on the non-priority road decreased compared with the conventional method of stopping before the intersection and then entering it after determining that it is safe to do so. If traffic volume is about 500 vehicles per hour, our method is more efficient than using traffic lights. In Japan, the average of the traffic volume is 440 vehicles per hour [12]. Therefore, the proposed method is effective at intersections with an average traffic volume. Moreover, it is effective even during the early stages of connected vehicles introduction because its efficiency is better than that using traffic lights when the penetration rate is 30% or more.

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.

In situations where there are both autonomous and human-operated vehicles, we found that safety can be ensured by setting the TTC sufficiently high to prevent surprising drivers of vehicles on the priority road. It is also possible to change the TTC more dynamically in accordance with other characteristics such as driver's age and vehicle type. In this study, only connected vehicles on the priority road judged whether it was safe for vehicles on the non-priority road to enter the intersection. A more advanced method would be to have the connected vehicles on the priority road transmit the TTC information to the connected vehicles on the non-priority road. This would enable a connected vehicle on the non-priority roads to take into account the vehicle's characteristics when judging whether it is safe for the vehicle to enter the intersection.

B. Disadvantages of the Proposed Method

This method would not work at intersections with heavy traffic on the priority road, such as many intersections in urban areas, because there are normally few breaks in the traffic flow that would allow vehicles on the non-priority road to enter the intersection. Another method is needed, such as the traffic lights method or a method in which connected vehicles on the non-priority road could transmit an entry request to connected vehicles on the priority road.

VII. CONCLUSION

Looking ahead to the time when connected and non-connected vehicles will share the road, we developed a method that enables connected vehicles on a non-priority road to traverse an intersection with a priority road more quickly on the basis of information in messages from connected vehicles on the priority road. An evaluation simulation designed to examine the safety and efficiency of connected vehicles on a non-priority road traversing an intersection showed that efficiency can be improved, and that safety can be ensured. We need further research and develop another method to make intersections with heavy traffic efficiency in the mixed situation.

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