STUDY ON COOPERATIVE CONTROL FOR MIXED TRAFFIC FLOW OF MANUAL AND AUTONOMOUS VEHICLES AT NON-SIGNALIZED INTERSECTION

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This paper proposed a cooperative control method at non-signalized intersection. All vehicles are assumed to be connected that information including position, speed and planned route can be aggregated in real time. Vehicles without conflict relationship are allowed to enter the intersection simultaneously, and their speeds are controlled by remaining safety distance and entry order. A microsimulation based on cellular automaton is carried out to compare the method with priority and signal control. The effects of traffic flow rate and penetration rate of autonomous vehicles are also examined. According to the results, the proposed method is effective with the increasing of penetration rate of autonomous vehicles, and more efficient than priority control under traffic flow rate that do not cause congestion. In addition, it is clarified that combining the method with priority or signal control can be considered as a countermeasure in the process of promoting autonomous vehicles.

Key Words : *cooperative control, microsimulation, cellular automaton, connected vehicle, non-signalized intersection*

1. INTRODUCTION

The aggravating trend of aging population and vehicle ownership have brought pressure to the current traffic system during the last two decades. Meanwhile, autonomous vehicles(AVs) have attracted more and more research interests, because their negligible reaction time delays and less headway requirement. Due to these characteristics, the road's capacity where AVs participate in is expected to increase, and AVs can also help with decreasing fuel consumption and emissions for a greener environment.

Recently, with the development of intelligent transportation systems(ITS), which represents the integration of information and communication technologies, the traffic management system has obtained the potential to be further improved in combination with AVs. Based on the new technology V2X(vehicle to everything), especially V2V(vehicle to vehicle) and V2I(vehicle to infrastructure), it is possible that this kind of connected vehicles can be guided by sharing their information about location, velocity and route to achieve the optimal statues.

Whereas, it is unrealistic to replace the vehicles to AVs all at once, that is to say manual vehicles(MVs) and AVs are supposed to travel together on the road at the early stage of employment. And it is no doubt that the penetration rate of AVs will influence the traffic efficiency. Hence, appropriate modeling approaches are needed to analyze the characteristics of such mixed traffic flow. However, this kind of studies are still limited so far.

Most studies have analyzed the control method for traffic flow which contains only AVs. Dresner and Stone built the simulation where AVs cross the intersection according to their arrival sequence, and other vehicles will decelerate to manage their arriving time[1)]. Li and Wang proposed the cooperative control method at blind intersections with inter-vehicle communication, that the best driving plans are searching by making a spanning tree to find each possible movement[2]. Lee and Park discussed the method about avoiding overlapping of vehicle trajectories, and declared it could not address the situation contained more than two conflicts[3]. Kamal et al. minimized the conflict risk by removing the conflicting vehicle away from the conflict point in the process of searching the most appropriate route[4]. Furthermore, Xu et al. proposed a cooperation method for connected vehicles at non-signalized intersections, in which vehicles without conflict relationship were allowed to enter the intersection simultaneously[5]. Vehicles are projected onto a virtual lane as a platoon and depth-first spanning tree algorithm is used to decide the sequence. Whereas, MVs are not considered and the method has not been evaluated.

On the other hand, a few studies analyzed mixed traffic flow including both MVs and AVs. Zheng et al. controlled the connected vehicles by calculating the conflicting possibility of every potential vehicles pairs to minimize the collision risk[6]. According to the result, the control method was effective when penetration rate of AVs exceeded 30%. However, the control rules for MVs were not separated from AVs and the interaction between them were not considered, which needed to be further explored.

This study aims to investigate a cooperative control method, which consider the interaction between MVs and AVs, and its performance will be evaluated by comparing to conventional control methods.

The rest of this paper is organized as follows. Section 2 describes the simulation environment based on cellular automaton. Section 3 explains the cooperative control method we proposed. Section 4 presents the simulation results along with the discussion. Finally, the study is concluded in section 5 and give some inspiration of future research direction.

2. SIMULATION ENVIRONMENT

Cellular automaton (CA) is a method that uses cells as basic units to describe the overall behavior of some complex systems. Due to its natural advantages for describing microscopic traffic flow characteristics easily by separating the space and vehicles on the road, CA theory is used in this study to simulate the mixed traffic flow.

CA method has been widely applied in traffic simulation. In the initial model proposed by Wolfarm, vehicles move forward as long as the front cell is empty without acceleration or deceleration rule[7),8]. Then, Nagel and Schreckenberg adopted the model by adding the acceleration and deceleration rule, for which the model was so called NaSch model[9]. It was employed in this study to display vehicles moving at various velocity.

(1) Network

The network used for cooperative control is showed as **Fig.1**.

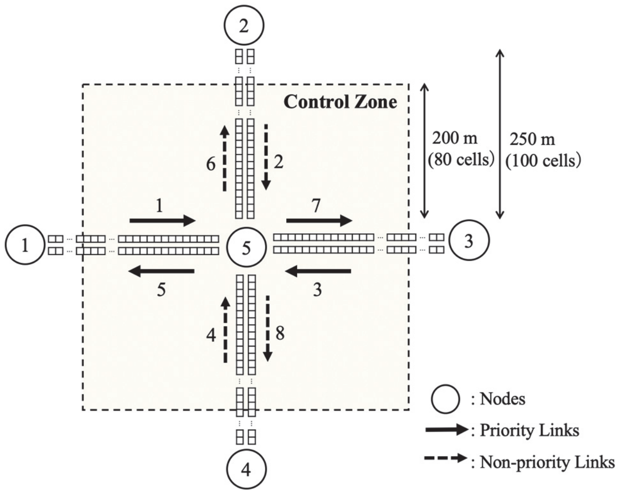


Fig.1 Network

The detailed information is as follows:

- Cell size = 2.5m.
- The length of link at all directions = 250m.
- Vehicles enter the network at node 1~4 and move on link 1~4. After passing through the intersection at node 5, vehicles move on link 5~8 and exit the network at node 1~4.
- The maximum velocity for each link = 45km/h.

Priority control is simulated on the same network by defining Link 1,3,5,7 as priority roads, and link 2,4,6,8 are non-priority roads (which are not considered in cooperative and signal control).

Besides, signalized intersection with right turn lane is defined as a comparison as shown in **Fig.2**. The right turn lane starts at 30m away from the intersection.

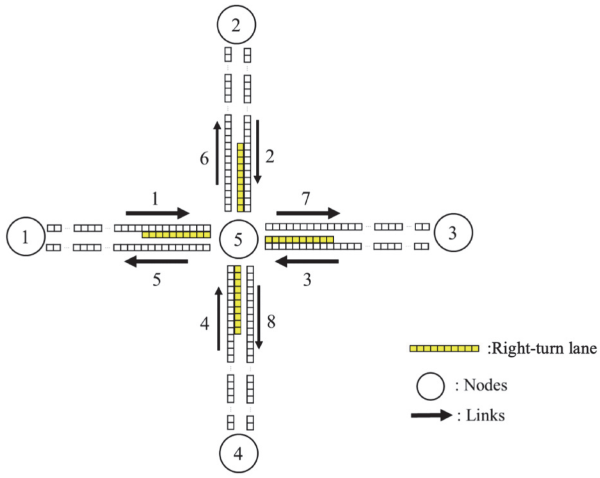


Fig.2 Network with right turn lane

(2) Local rules in simulation

The time interval of CA model is set as 1s, which means the system will be updated every second, so the distance(m) traveled by vehicle equals to its velocity(m/s). The local update rules are described in four categories, including vehicles' generation, velocity, lane change behavior and movement between links.

a) Generation rule

The OD generated in 10 minutes is used as the basic value, so OD in one hour will be 6 times of the value. Then, they are assigned to node 1-4, respectively. The departure time of each vehicle will be given randomly, and their ID is set according to the departure time. Dijkstra method is utilized here to find the shortest route[10].

b) Velocity rule

The velocity v of each vehicle is updated according to the maximum velocity $v_{\max}$ on the current link and the distance gap to the front vehicle:

- When $v \geq gap$, $v = gap - \mathrm{p_{noise}}$;
- When $v < v_{\max}$, $v = v + 1 - \mathrm{p_{noise}}$;
- Otherwise, $v = v - \mathrm{p_{noise}}$.

Here, $\mathrm{p_{noise}}$ illustrates the uncertainty in MVs, which will be given as -1, 0 or 1 based on the random probability p. After the adjustment, the velocity will be confirmed again to avoid collisions.

c) Lane change rule

In this study, although each link is a two-way lane (single lane for one direction), lane change can occur on the network with right turn lane which is showed as **Fig.2**. Whether the vehicle will change lane or not will be decided by $weight1{\sim}5$. Here, gap_o and gap_b imply the gap with the front car and rear car on the adjacent lane respectively, d is the numbers of cells to the intersection.

- $weight1 = 1$ when side cell is empty, $gap < v$ and $gap_o > gap$, otherwise $weight1 = 0$.
- $weight2 = max[v - gap_o, 0]$, $weight3 = max[v_{max} - gap_b, 0]$.
- $weight4 = max\left[\frac{d^* - d}{v_{max}}, 0\right]$, which describes the urgency degree which increases along with the vehicle moving close to the intersection. In this study, d^*=26 to make sure $weight4$ starts to be effective at 200m from the intersection.
- $weight5 = weight1 + weight4$, which means vehicles located between half of the link and 30m from the intersection will change lane when $weight5 > weight2$ and $weight5 >$ weight3.

Each vehicle follows the route decided at the departure time, and it should stay at the proper lane in order to enter the next link.

d) Movement between links

Three types of control methods are compared in this study including cooperative, priority and signal control. Movement rules for the latter two methods are explained here and the rules for cooperative control will be supplemented in section 3.

As for vehicles on priority road, they can move to the next link, when the first cell on next link is empty and no other vehicles with higher priority exist within critical gap. The vehicle go straight at the intersection can pass without deceleration, others should decelerate to 10km/h. As for those on non-priority road, the rules are similar except each vehicle must stop at the intersection before it enters.

Regarding the signalized intersection, when the light is green, the vehicles go straight can pass the intersection directly, while vehicles make turns should decelerate to 10km/h. When the light is red, all vehicles wait until it turns green. When the light is yellow, the decision whether pass or stop at the intersection will be made based on the current velocity and distance from the intersection. The decision process can be described by two functions:

$$L_1 = \tau v + \frac{v^2}{2r} \tag{1}$$

$$L_2 = Yv \tag{2}$$

Where, v is the velocity when the light turns yellow, r is deceleration(2.5m/s^2), τ is the reaction time(1.0s), Y is the yellow time(3s).

L_1 defines the braking distance at normal deceleration, L_2 defines the distance traveled at v during the yellow time. **Fig.3** shows two curves which divides the figure into 4 areas.

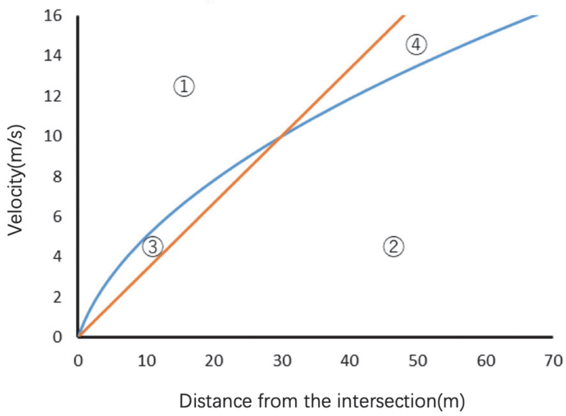


Fig.3 Movements at yellow light

The meaning of each area is explained as follows:

①Vehicles can pass the intersection safely at current velocity.

②Vehicles can stop at the intersection safely by deceleration.

③Vehicles can pass the intersection safely at current velocity, and stop at the intersection safely by deceleration as well. (Option zone)

④Vehicles cannot pass the intersection at current velocity before the light turns red, or stop at the intersection by normal deceleration. (Dilemma zone)

In situation①and②, the movements can both be achieved safely during the yellow time. As for option zone and dilemma zone, the possibility of the vehicle chooses to pass or stop at the intersection is both set as 50%.

(3) Signal control

In this study, signal control with and without right turn lane are both discussed. The optimum cycle time C_p is given by Webster signal design method[11]:

$$C_p = \frac{1.5L + 5}{1 - \lambda} \tag{3}$$

where, L is total lost time per cycle(s),

$$L = 2n + R \tag{4}$$

where, n = number of phases, R = all red time. Besides, $\lambda = \sum_1^n \lambda_i$ and $\lambda_1 = \frac{q_1}{s_1}$: q = design flow rate per lane(veh/h), s = saturation flow rate per lane(veh/h).

The simulated signal plan in this study contains two phase, and all red interval = 2s, yellow time = 3s. Therefore, green time of phase 1 can be obtained by:

$$G_1 = \frac{\lambda_1}{\lambda}(C_p - L) \tag{5}$$

Green time of phase 2 can be calculated in the same way.

(4) Different rules for AVs and MVs

In the simulation, noise, safe distance and critical gap are given to reflect different performance of AVs and MVs.

a) Noise

Parameter p_{noise} is introduced here to describe the speed uncertainty of manual drivers. For AVs, p_{noise} is always set as 0.

According to Kockelman and Ma, the variability of velocity increases with the average velocity, which can be defined as[12]:

$$\sigma = 0.095v \tag{6}$$

The probability of p_{noise}'s value is summarized in the follow table.

Table 1 Probability of p_{noise}'s value

Velocity	Probability of p_{noise}'s value (%)		
	-1	0	1
9 km/h	0.00	100	0.00
18 km/h	0.42	99.16	0.42
27 km/h	3.97	92.06	3.97
36 km/h	9.41	81.18	9.41
45 km/h	14.63	70.74	14.63

b) Safe distance

As for AVs, smaller distance is allowed between successive vehicles. However, in the mixed traffic flow, four types of vehicle pairs should be considered.

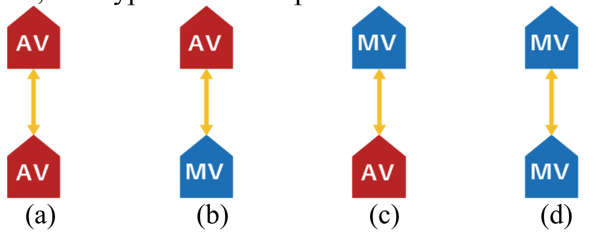


Fig.4 Relationships between vehicle pairs

Here, relationship (a) which only contains AVs can have minimum safe headway 5.0 m (2 cells), and others are set as 7.5m (3 cells).

c) Critical gap

According to U.S. HCM 2000, critical gap is defined as minimum time between successive major stream vehicles, in which minor street vehicle can make a maneuver. In this study, it restricts the arrival time between vehicles which try to enter the intersection. For AV pairs, the critical gap is set as 2s, others are set as 3s to reflect the difference.

(5) Evaluation

To confirm whether the simulation can perform appropriately with the rules described above, a simple network is set to verify its feasibility, i.e. a single lane, one-way circular road showed in **Fig.5**.

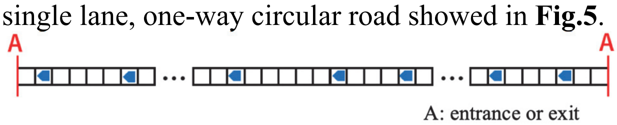


Fig.5 A single lane circular road

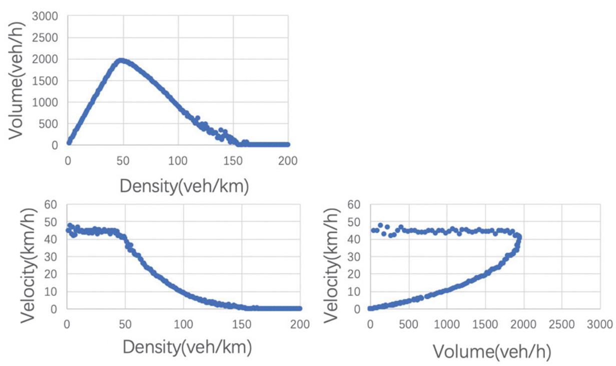


Fig.6 Fundamental diagram at AVs=0%

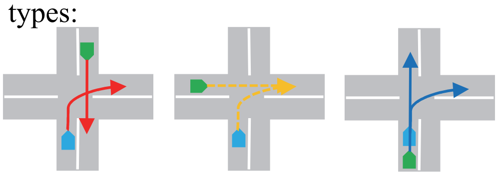
Fig.6 shows the fundamental diagram when the penetration rate of AVs is 0%. It presents familiar shape to the triangular fundamental diagram and the road capacity is about 2000veh/h which is close to the desired single lane traffic capacity (2200veh/h). Therefore, the simulation proposed can properly represent the traffic flow.

3. COOPERATIVE CONTROL ALGORITHM

To allow vehicles pass the intersection safely and efficiently, the depth-first spanning tree algorithm proposed by Xu et al.[5] finds conflict-free vehicles and determine the order each vehicle's entrance to the intersection to let them pass simultaneously. In addition, it is assumed that the traffic control system is equipped at each intersection and order each vehicle to adjust their velocity. Both AVs and MVs can receive the instruction from that control system. It is assumed that AVs can follow the instruction exactly, while MVs try to follow but its maneuver includes uncertainty. In this study, the algorithm is adopted to manage the mixed traffic flow contains both AVs and MVs, and its performance is evaluated by the comparison with priority and signal control.

(1) Spanning tree

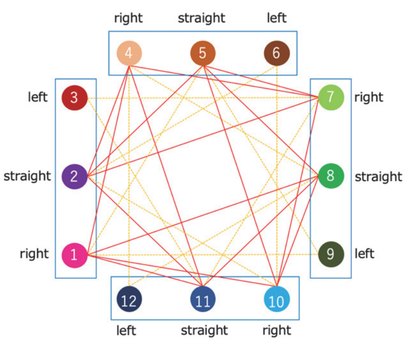
Firstly, conflict relationship is categorized into three types:



(a) Crossing (b) Merging (c) Diverging

Fig.7 Conflict relationship

To avoid collision, vehicles have conflict relationship showed in **Fig.7** cannot enter the intersection simultaneously. In this study, the network is made up with a single intersection of four links. The relationship of all possible movements is summarized in **Fig.8**, in which red line presents crossing, yellow line presents merging and the area in blue rectangle is diverging. $\mathbb{C}_n$: the collection of movements which conflict with movement *n*.



$\mathbb{C}_1 = \{1,2,3,4,5,8,9,10,11\}$
$\mathbb{C}_2 = \{1,2,3,4,5,6,7,10,11\}$
$\mathbb{C}_3 = \{1,2,3,7,11\}$
$\mathbb{C}_4 = \{1,2,4,5,6,7,8,11,12\}$
$\mathbb{C}_5 = \{1,2,4,5,6,7,8,9,10\}$
$\mathbb{C}_6 = \{2,4,5,6,10\}$
$\mathbb{C}_7 = \{2,3,4,5,7,8,9,10,11\}$
$\mathbb{C}_8 = \{1,4,5,7,8,9,10,11,12\}$
$\mathbb{C}_9 = \{1,5,7,8,9\}$
$\mathbb{C}_{10} = \{1,2,5,6,7,8,10,11,12\}$
$\mathbb{C}_{11} = \{1,2,3,4,7,8,10,11,12\}$
$\mathbb{C}_{12} = \{4,8,10,11,12\}$

Fig.8 Conflict relationship of all movements

According to the distance to the intersection, depth-first spanning tree algorithm projects vehicles in different movements into a virtual platoon with number 1~*N* which is showed in **Fig.9**. A virtual leading vehicle 0 with constant velocity is assigned to the beginning of the platoon.

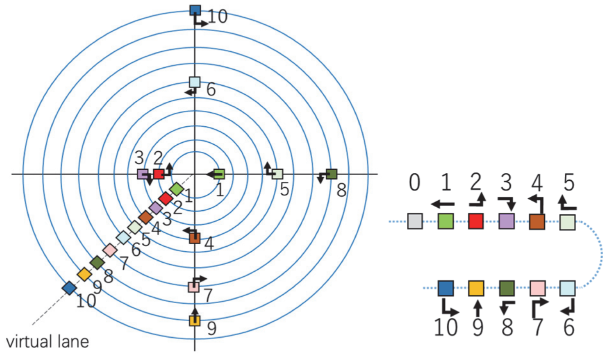
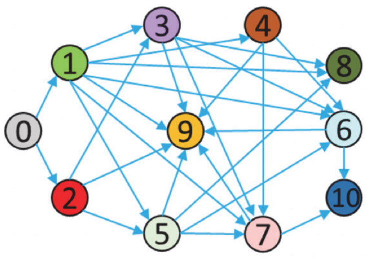


Fig.9 Example of projecting a virtual platoon

Fig.10. shows the conflict relationship of vehicles shown in **Fig.9**. $\mathbb{P}_\mathrm{i}$ is defined as conflict vehicle set which consists of all vehicles have conflict relationship with vehicle *i* and travel ahead of it. Therefore, the $\mathbb{P}_\mathrm{i}$ for the example showed above can be obtained as:



$\mathbb{P}_1 = \{0\}$
$\mathbb{P}_2 = \{0\}$
$\mathbb{P}_3 = \{1,2\}$
$\mathbb{P}_4 = \{1\}$
$\mathbb{P}_5 = \{1,2\}$
$\mathbb{P}_6 = \{1,3,4,5\}$
$\mathbb{P}_7 = \{1,3,4,5\}$
$\mathbb{P}_8 = \{1,3,5\}$
$\mathbb{P}_9 = \{1,2,3,4,5,6,7\}$
$\mathbb{P}_{10} = \{6,7\}$

Fig.10 Conflict relationship graph

In the directed graph shown in **Fig.10**, the vertexes represent the vehicles and the directed edges indicate the conflict relationship between them. The spanning tree can be made by the following process:

① The depth of vehicle 0 is set as 0, i.e. $d_0 = 0$.
② Do loop according to the vehicle number *i*=1, 2, 3, …, *N*.
③ Find all ancestors in set $\mathbb{P}_i$.
④ Find the largest depth d_k among the ancestors.
⑤ Add the vertex *i* and edge (*k*, *i*) to the graph, and $d_i = d_k + 1$.
⑥ Go back to step 3 until *i*=*N*.

The spanning tree of the example can be made as:

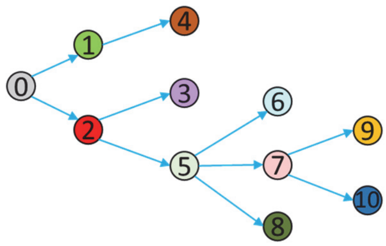


Fig.11 Spanning tree

In this study, the process begins when the vehicle enters the control zone (200m away from the intersection), and new vehicle ID will be given according to its order on the virtual lane. Then the depth of the vehicle is decided one by one based on their new ID. If a new vehicle enters the control zone, instead of making the whole spanning tree again, we only need to find its ancestor and determine the depth by step 3-5.

(2) Constraints

In the spanning tree, vehicles at the same depth can enter the intersection simultaneously without conflict. Whereas, to ensure the safety and efficiency of vehicles in different depths, other constraints should be considered.

a) Maximum velocity in the control zone

In this study, the maximum velocity of the network is defined as 45km/h. Due to vehicles plan to turn right or left should slow down before the intersection, the vehicles go straight in the same depth will decelerate to maintain the group location. Hence, the maximum velocity follows the restriction in **Table 2**.

Table 2 Maximum velocity in cooperative control

Distance from the intersection	Maximum velocity
50-200 m	45 km/h
25-50 m	36 km/h
0-25 m	27 km/h
0 m go straight	27 km/h
0 m turn right	9 km/h

b) Car following Distance *D*

The cooperative control method is executed by managing the velocity.

For the vehicle group closest to the intersection, it travels at the maximum velocity defined in **Table 2**. For other groups, they should travel with keeping a proper distance D to the last car of their ancestors. And the velocity is managed based on the distance between its current location and the location of its ancestor at next step.

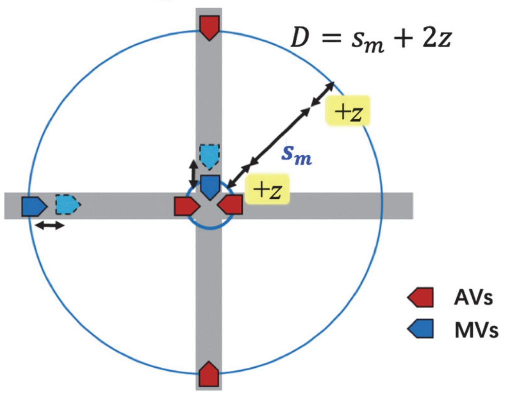


Fig.12 The distance D between successive group

In **Fig.12**, s_m is the braking distance and parameter z is introduced to describe the distance fluctuation resulted from uncertainty of manual driver's maneuver. As long as MV existing in the successive groups, z should be considered at the side which contains MV.

Since the noise for velocity is calculated at 95% confidence interval, z is defined as follows:

$$z = 1.96\sigma \qquad (7)$$

where σ can be obtained by formula (6) and rounded value of z is used in simulation as shown in **Table 3**.

Table 3 Value of z

Velocity	z	
	AVs only	MVs
0-18km/h	0 m	0 m
27-45km/h	0 m	2.5 m

Therefore, the car following distance D on the virtual lane is decided by three rules:

① Distance to the intersection: as it has mentioned in section 2.(4) c), the critical gap is 2s for AVs and 3s for mixed traffic flow, the maximum velocity is 27km/h when vehicles close to the intersection, so that the distance should be kept more than 15m or 27m.

② Keep safety distance: when the vehicle velocity is v, the braking distance s_m can be calculated from:

$$s_m = l + 0.278v + 0.00394\frac{v^2}{f} \qquad (7)$$

where, l is the length of the vehicle (m), f indicates the road friction. The reaction time in function (7) is 1s, which can be smaller when only AVs travel on the road. According to Bernhard F., the reaction time is 0.5s for AVs[13], and the function can be updated as:

$$s_m = l + 0.278v + 0.00394\frac{v^2}{f} - (1 - 0.5)v \qquad (8)$$

③ Considering the change of maximum velocity explained in (2) a) of this section.

According to these rules, the value of D can be summarized in **Table 4**.

Table 4 Distance D for cooperative control

Distance from the intersection	Distance D	
	AVs only	Mixed traffic flow
50-200 m	20 m	27.5 m
25-50 m	17.5 m	25 m
0-25 m	15 m	22.5 m

c) Minimum velocity

During the simulation, we found that vehicles tend to wait at the entrance of control zone until its distance to the ancestors satisfies with D, which reduces the efficiency. Hence, the minimum velocity is applied for vehicles to reach distance D while driving. On the other hand, the minimum velocity shouldn't be too large which may cause vehicles to queuing before the intersection. The minimum velocity used in the study is showed in **Table 5**.

Table 5 The most proper minimum velocity

Distance from the intersection	Minimum velocity	
	AVs only	Mixed traffic flow
75-200 m	27 km/h	18 km/h
50-75 m	18 km/h	9 km/h
25-50 m	9 km/h	9 km/h
0-25 m	0 km/h	0 km/h

4. RESULTS AND DISCUSSION

To verify the cooperative control method proposed in section 3, priority and signal control are utilized as comparing objects in the simulation. And for signal control, both network with and without right turn lane are simulated. The efficiency of these control methods is evaluated by average travel time per vehicle.

Traffic flow rate used here is set with reference to the Kichijoji, Mitaka benchmark data set, which contained the real traffic data of the intersection located at Seikei-dori[14]. The basic volume is 1800 veh/h and both right and left turn ratios are set as 10%. To evaluate the method, cases where the traffic flow rate are larger or fewer than 1800 veh/h are also simulated.

Firstly, **Fig.13** displays the result at different traffic flow rate when penetration rate of AVs=100%.

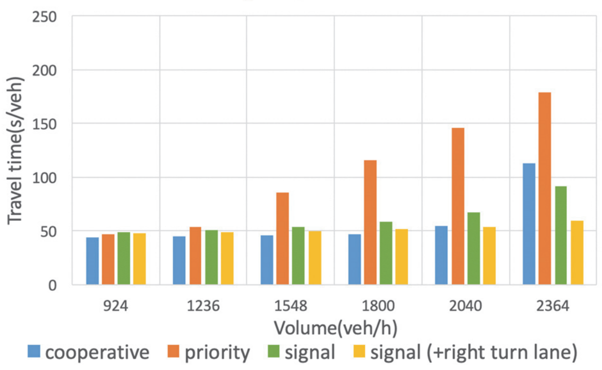
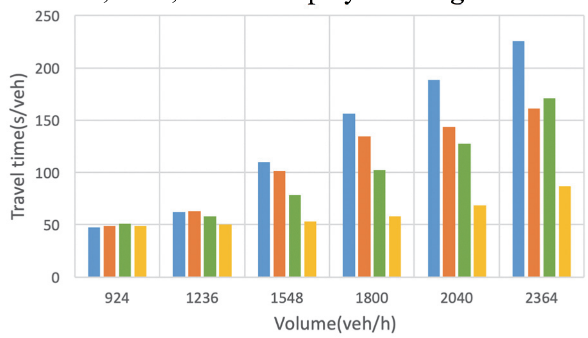


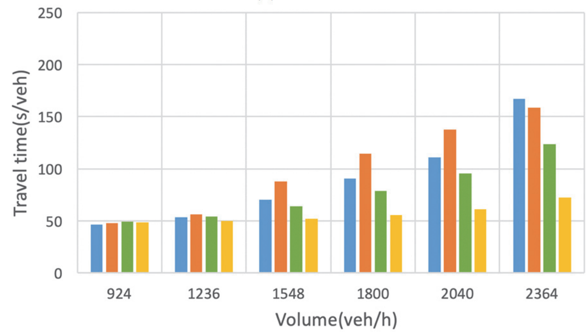
Fig.13 Travel time (AV=100%)

The figure shows that if traffic flow rate is no more than about 2000veh/h, cooperative control results in the least travel time among four methods. When the traffic is at free flow, for example volume=924veh/h, the travel time is about 40s and the average speed can be calculated as 45km/h, which equals to the maximum velocity of the network. Therefore, the proposed method is proved to work efficiently.

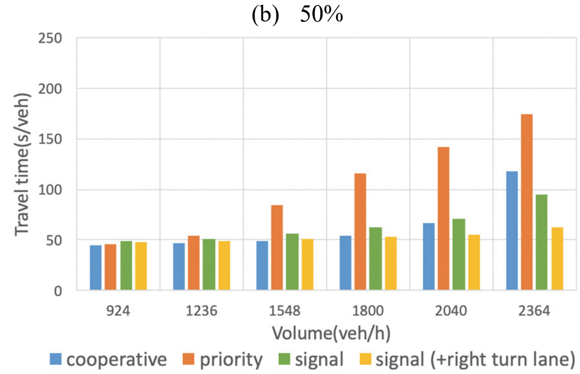
Then, the travel time at different penetration rate=20%, 50%, 80% is displayed in **Fig.14**.



(a) 20%



(b) 50%



(c) 80%

Fig.14 Travel time at different volume

Along with the increasing of penetration rate of AVs, the travel time decreases for the same volume. On the network with right turn lane, the travel time of signal control doesn't change much, and has stable performance especially at large traffic flow rate. To find out the most efficient control method among these four, **Fig.15** is made to select the best method at specific volume and penetration rate.

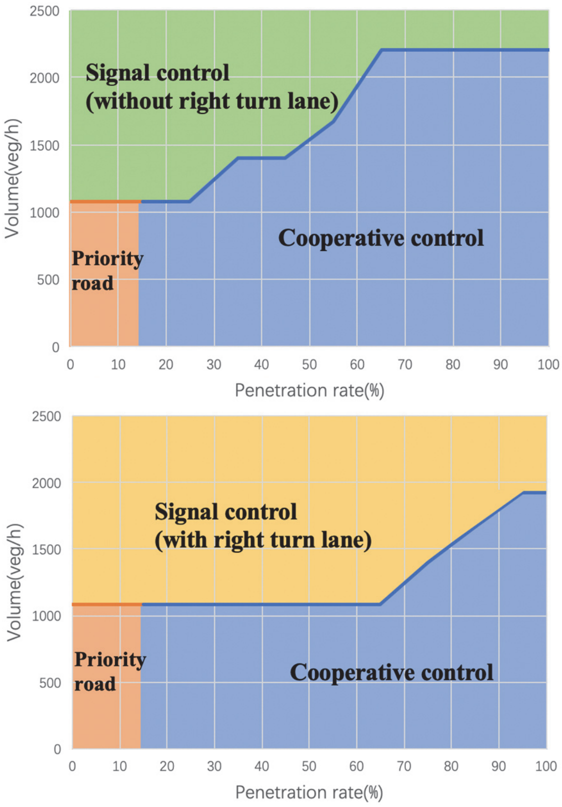


Fig.15 The most efficient control method

Since the simulation process repeats 30 times to get the average value under different scenarios, **Fig.16** is plotted to show the standard deviation of the data. When traffic flow rate is less than 2000veh/h, standard deviation decreases with the increasing of penetration rate, which indicates the traffic status tends to be stable. On the other hand, the standard deviation remains high when the road is congested.

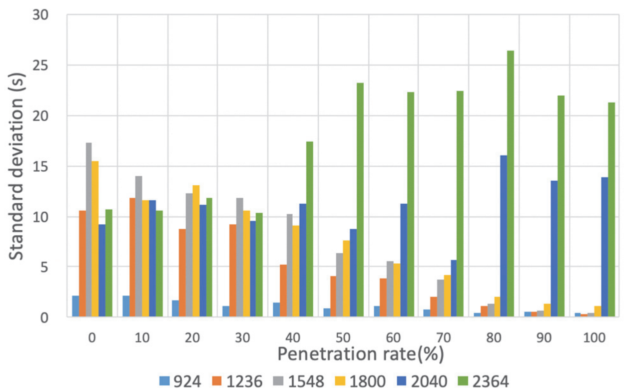


Fig.16 Standard deviation of cooperative control

Based on the simulation results above, the performance of proposed cooperative control method can be summarized in the following aspects:

The performance is evaluated by comparing with other two conventional control methods, priority and signal control. As all vehicles in the simulation are assumed as connected vehicles, they can share information and follow the instructions to choose the most appropriate route. The difference between AVs and MVs is that uncertainty exists in manual drivers' behavior and the suggested velocity may not be achieved perfectly. Hence, from the simulation at different volume, the efficiency of proposed method improves significantly with the increasing of penetration rate. On the other hand, the penetration rate has few influences on priority or signal control method. Especially, when traffic flow rate is less than 1800veh/h, both of them have stable performance.

Regarding the penetration rate, the proposed method is found to become effective only when the rate of AVs on the road beyond a certain value. According to **Fig.15**, the advantages mainly start to emerge when penetration rate beyond 15%. However, signal control has good performance on managing the large traffic flow rate, which can be utilized to make collaboration with the proposed method.

5. CONCLUSION

In this paper, a cooperative control method is proposed and simulated at a non-signalized intersection. All vehicles in the simulation are supposed to be connected vehicles, which can be categorized into two types: AVs and MVs. And the performance of proposed method is evaluated not only numerically, but also by the comparison with traditional methods: priority and signal control.

From the simulation result, it is found that the proposed cooperative method can manage the traffic efficiently, and has better performance than other methods when the penetration rate is larger than 15%. Besides, when the road become congested, signal control method has the best and most stable performance. Since it is difficult to achieve a high penetration rate at the very earliest stage, the cooperation between signal control and the proposed method can be considered as a countermeasure.

Whereas, the simulation result can only reflect the situation of single non-signalized intersection mentioned in this paper. And the control rules about maximum velocity and distance between successive vehicles may not be the most proper value, so further exploration is needed. Another limitation is that in the process of making the spanning tree, overtaking is not allowed between different generations. The vehicle can only become the member of the existing youngest generation or the leader of a new generation when it enters the control zone. Hence, for future work, the employment on larger and more complicated network is expected. In addition, the proposed method can be optimized by allowing the overtaking between different generations, which helps with increasing the number of vehicles which can passing the intersection simultaneously.

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