Investigation of a Scheduling Scheme for Cooperative Merging at a Highway On-Ramp with Maximizing Average Speed of Automated Vehicles

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Abstract: Recently, connected and automated vehicles have potential to mitigate traffic congestion and improve traffic efficiency at a highway on-ramp. The state-of-the-art scheme improves traffic efficiency by assigning timing of merging to automated vehicles on roads by minimizing total travel time of them. The scheme, however, causes traffic congestion when inflow traffic becomes high because of the characteristic that the scheme makes groups of vehicles on the same road. Since length of the groups of vehicles becomes too long as inflow traffic becomes high, this length should be short by decreasing density of vehicles on roads in order to mitigate traffic congestion. In this paper, we show investigation of a scheduling scheme for cooperative merging at a highway on-ramp with maximizing average speed of automated vehicles. Based on traffic model that density and speed of vehicles have a negative correlation, we maximize speed of vehicles in order to decrease density of vehicles. Furthermore, we consider fairness between both the main and ramp road in terms of traffic efficiency by utilizing difference of average speed of vehicles on both the main and ramp road. Simulation result shows that the proposed scheme increases outflow traffic from a highway on-ramp by 400 (veh/h) at most in comparison with related schemes when inflow traffic becomes 2000 (veh/h). Furthermore, simulation result shows that the proposed scheme decreases density of vehicles.

1. Introduction

Recently, traffic congestion has been regarded as a problem to be resolved. In 2014, traffic congestion caused people to spend 6.9 billion hours in urban areas [1]. Moreover, traffic congestion produces driver discomfort, distraction, and frustration [2]. The uncomfortable feeling causes aggressive driving behavior and slows the process of recovering smooth traffic flow [3]. One of the source of traffic congestion is merging into highway on-ramps. Since multiple inflow traffic concentrates at a highway on-ramp, drivers have to drive carefully. The careful driving decreases speed of vehicles and causes traffic congestion. Hence, highway merging is regarded as a bottleneck of traffic [4].

One of the common schemes to mitigate traffic congestion at highway on-ramps is a ramp metering scheme [5]. A ramp metering scheme utilizes a traffic light at a highway on-ramp and regulates vehicles on a road merging into another road. However, this scheme forces vehicles to stop nearby a highway on-ramp, and vehicles are forced to do stop-and-go driving. This movement causes a wave of stop-and-go traffic, which is a reason of traffic congestion [6]. With the development of Vehicle to Vehicle (V2V) and Vehicle to Infrastructure (V2I) communication, Connected and Automated Vehicles (CAVs) have potential to mitigate traffic congestion and improve traffic efficiency [7]. Since V2V communication enables CAVs to share when to merge into a highway on-ramp among vehicles on roads, CAVs are able to manipulate timing of merging into a highway on-ramp. Hence, CAVs are able to avoid undesirable stop-and-go driving. Several approaches that utilize V2V communication have been proposed [8,9], and several approaches that utilize V2I communication have been proposed in order to ensure optimality of traffic efficiency [10, 11]. The state-of-the-art scheme minimizes total travel time of automated vehicles and improves outflow traffic from a highway on-ramp by assigning timing of merging to them [11]. However, this scheme causes traffic congestion when inflow traffic becomes high because of the characteristic that it makes group of vehicles on the same road. Specifically, when the inflow traffic becomes high, the length of the group of vehicles becomes too long and traffic congestion occurs. Since this traffic congestion prevents vehicles from merging into a highway on-ramp smoothly, density of vehicles should be decreased by assigning timing of merging to automated vehicles.

In this paper, we show investigation of a scheduling scheme for cooperative merging at a highway on-ramp with maximizing average speed of automated vehicles. Based on traffic model that density and speed of vehicles have a negative correlation, we maximize speed of vehicles in order to decrease density of vehicles. Furthermore, we consider fairness between both the main and ramp road in terms of traffic efficiency by utilizing difference of average speed of vehicles on both the main and ramp road.

The rest of this papers is organized as follows: Section 2

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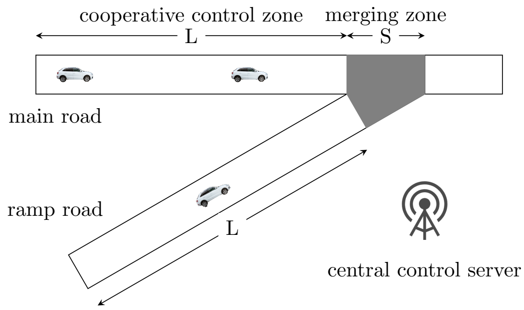

Fig. 1: A common scenario for vehicles merging into a highway on-ramp

Table 1. DEFINITIONS OF VARIABLES

variable	definition
V_i	an expression of vehicle i
V	a set of all vehicles on roads
V_{main}	a set of vehicles on main road
V_{ramp}	a set of vehicles on ramp road
d_i	distance from vehicle i to a merging zone
v^i_{max}	maximum speed of vehicle i
v^i_{min}	minimum speed of vehicle i
v^i_{now}	current speed of vehicle i
a^i_{max}	maximum acceleration of vehicle i
a^i_{min}	minimum acceleration of vehicle i
t^i_{assign}	assigned timing of vehicle i
t^i_{max}	upper bound of t^i_{assign}
t^i_{min}	lower bound of t^i_{assign}
t_{head}	minimum safety headway in the same road
t_{guard}	minimum safety headway in different roads
t_{now}	current time
S	length of a merging zone
L	length of a cooperative control zone

presents the proposed scheme. Section 3 shows evaluation results. Section 4 concludes this paper.

2. Proposed Scheme

In order to decrease density of vehicles on roads and improve outflow traffic from a highway on-ramp, we show investigation of a scheduling scheme for cooperative merging at a highway on-ramp with maximizing average speed of automated vehicles. Based on traffic model that density and speed of vehicles have a negative correlation, we maximize speed of vehicles in order to decrease density of vehicles. Furthermore, we consider fairness between both the main and ramp road in terms of traffic efficiency by utilizing difference of average speed of vehicles on both the main and ramp road.

2.1 System Model

Figure 1 shows a common scenario for vehicles merging into a highway on-ramp. Definitions of variables are explained in Table 1. The scenario consists of vehicles and a central control server. All vehicles are assumed to be autonomous and they are equipped with On-Bord Units (OBU) that are able to communicate with a central control server through IEEE 802.11p protocol [12]. In addition, the central control server is able to control vehicles which is inside a cooperative control zone. When vehicles enter a cooperative control zone, they start to send information of them to a central control server. By using this information, the server calculates and schedules optimal timing of vehicles to merge into a highway on-ramp at regular intervals. After the calculation, the server sends the optimal timing to vehicles. When vehicles receive the optimal timing, they manipulate their speeds to reach the merging zone at their merging timing. Specifically, when distance between a vehicle and vehicles in front of it is less than safe following distance, the vehicle follows the ones in front of it. Otherwise, the vehicle runs freely.

2.2 Proposed Objective Function

In this section, we explain the proposed objective function. In order to decrease the density of vehicles, we utilize relation between density of vehicles and speed of vehicles. Based on Green Sheelds traffic model, density and speed of vehicles have negative correlation [13]. Hence, density of vehicles k is expressed as follows,

$$k = -\alpha v + \beta, \quad s.t. \quad 0 < \alpha, 0 < \beta \tag{1}$$

where v is speed of vehicles, and α and β are constant values, respectively. In the proposed scheme, we use average speed of vehicles as representative value of speed of vehicles. Here, the objective function F is formulated as

$$F = \frac{1}{|V|} \sum_{i \in V} \frac{d_i}{t^i_{assign} - t_{now}}, \tag{2}$$

where V, d_i, and t_{now} denote a set of all vehicles on roads, distance from vehicle V_i to a merging zone, and current time, respectively.

Although the proposed scheme decreases density of vehicles on whole roads, it does not ensures fairness between both the main and ramp road in terms of traffic efficiency. In other words, there is possibility that maximization of the average speed of vehicles may preferentially allocates timing of merging to vehicles only on one road. In order to ensures the fairness between both the main and ramp road in terms of traffic efficiency, difference between speeds of vehicles on both the main and ramp road should be decreased. In this scheme, we use average speed of vehicles on a main and a ramp road as representative values. Here, the difference between average speed of vehicles on both the main and ramp road is expressed as

$$\left| \frac{1}{|V_{main}|} \sum_{i \in V_{main}} \frac{d_i}{t^i_{assign} - t_{now}} - \frac{1}{|V_{ramp}|} \sum_{i \in V_{ramp}} \frac{d_i}{t^i_{assign} - t_{now}} \right|, \tag{3}$$

where V_{main} and V_{ramp} denote a set of vehicles on a main road and a set of vehicles on a ramp road, respectively. Finally, the objective function which considers both the traffic efficiency on whole roads and the traffic efficiency on each road is formulated as

Table 2. SIMULATION PARAMETERS

name (variable)	value
length of a cooperative control zone (L)	400 (m)
length of a merging zone (S)	10 (m)
speed of a vehicle (v)	[1.0, 60.0] (km/h)
acceleration of a vehicle (a)	[-4.5, 2.6] (m/s^2)
ratio of inflow traffic of ramp road to inflow traffic of a main road (r_{main})	$[0.05, 1.00]$
inflow traffic of a main road (f_{in}^{main})	1000 (veh/h)
inflow traffic of a ramp road (f_{in}^{ramp})	$f_{in}^{main} * r_{main}$ (veh/h)
ratio of minimum headway in the same road to minimum headway in different roads (r_{guard})	$[0.05, 1.00]$
minimum headway in different roads (t_{guard})	4 (sec)
minimum headway in the same road (t_{head})	$t_{guard} * r_{guard}(sec)$
a segment of a road (l_{seq})	100(m)
weight of average speed of all vehicles (w_1)	0.5, 1.0
simulation time ($T_{simulation}$)	2000 (sec)

$$
\begin{aligned}
F =& w_1 \frac{1}{|V|} \sum_{i \in V} \frac{d_i}{t^i_{assign} - t_{now}} \\
& - w_2 \left| \frac{1}{|V_{main}|} \sum_{i \in V_{main}} \frac{d_i}{t^i_{assign} - t_{now}} \right. \\
& \left. - \frac{1}{|V_{ramp}|} \sum_{i \in V_{ramp}} \frac{d_i}{t^i_{assign} - t_{now}} \right| \\
s.t. \quad & w_1 + w_2 = 1.0,
\end{aligned} \tag{4}
$$

where w_1 and w_2 denote weight of average speed of all vehicles and weight of difference between average speed of vehicles on a main road and that of a ramp road, respectively. When value of w_1 is close to 1.0, the proposed scheme assigns timing of merging to vehicles to decrease density of vehicles on whole road. Otherwise, when value of w_1 is close to 0.0, the proposed scheme assigns timing of merging to vehicles to decrease to decrease difference between average speed of vehicles on both the main and ramp road.

3. Evaluation

In order to evaluate the effectiveness of the proposed scheme, the proposed scheme (Proposed) is compared with the First-In-First-Out based scheme (FIFO) [10] and the state-of-the-art scheme as Previous scheme (Previous) [11]. Specifically, FIFO scheme assigns timing of merging to vehicles in order of distance from them to a merging zone. All the simulation is carried out by using Simulation of Urban Mobility (SUMO 1.1.0), which is an open-source micro traffic simulator. The calculation in a central control server is done by using programming language Python2.7 and performed on a computer which has Intel Core i7, 3.1 GHz processor and 16 GB memory. The key simulation parameters are shown in Table 2.

In this simulation, we evaluate outflow traffic from a highway on-ramp and density of vehicles on roads. These evaluation metrics are evaluated by 2 scenario which are as follows,

- Scenario 1: evaluation by changing the value of r_{main},
- Scenario 2: evaluation by changing the value of r_{guard}.

We run the simulation 5 times for each value of r_{main} and r_{guard}, and average values of these evaluation metrics are plotted in the simulation results.

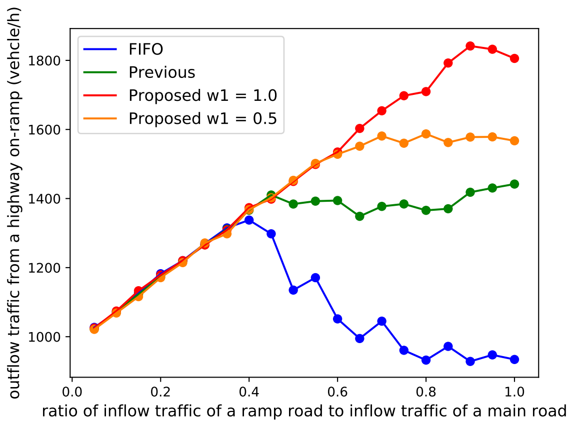

Fig. 2: Outflow traffic from a highway on-ramp vs ratio of inflow traffic of a ramp road to inflow traffic of a main road r_{main}

3.1 Scenario 1

In this scenario, evaluation metrics of each scheme are evaluated by changing r_{main} from 0.05 to 1.00. In other words, total inflow traffic changes from 1050 (veh/h) to 2000 (veh/h). The minimum headway in the same road t_{head} is fixed to 1 (sec) which is sufficient minimum headway for autonomous vehicles [14].

3.1.1 Outflow Traffic from Highway On-Ramp vs r_{main}

Figure 2 shows outflow traffic from a highway on-ramp vs ratio of inflow traffic of a ramp road to inflow traffic of a main road r_{main}. As show in Fig. 2, outflow traffic of the proposed scheme with $w_1 = 1.0$ is larger than that of previous scheme by 400 (veh/h) at most when r_{main} is 1.0. In contrast, outflow traffic of the previous scheme is lower than that of the proposed scheme. This is because the previous scheme does not ensure the optimality for the outflow traffic. Although the previous scheme ensures to minimize total travel time of vehicles, density of vehicles of the previous scheme becomes larger than that of the proposed scheme as r_{main} becomes high. As a result, the previous scheme causes traffic congestion, and the traffic congestion prevents vehicles on roads from merging into a highway on-ramp smoothly. Outflow traffic of the FIFO scheme decreases as r_{main} increases. This is because FIFO scheme alternately assigns merging timing to vehicles on both the main and ramp road in order of distance from them to a merging zone. As a result, frequency of appearance of t_{guard} becomes higher as the inflow traffic of a ramp road r_{main} increases. Since t_{guard} is longer than t_{head}, outflow traffic of the FIFO scheme decreases as frequency of appearance of t_{guard} becomes high.

3.1.2 Density of Vehicles vs Time in A Simulation

In order to show influence on density of vehicles when inflow traffic of a ramp road is high, we fix the value of r_{main} to 0.7 and evaluate density of vehicles at time in a simulation.

Figure 3 shows density of vehicles on both the main and

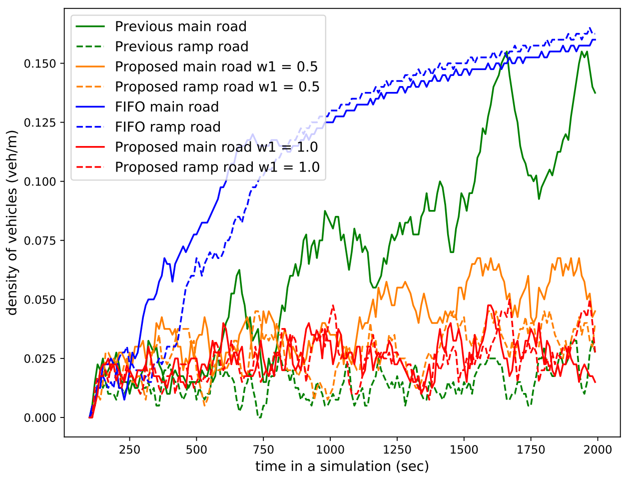

Fig. 3: Density of vehicles on both the main and ramp road vs time in a simulation

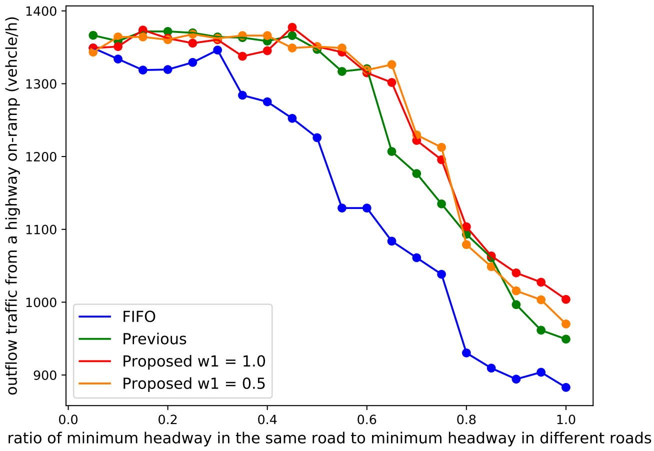

Fig. 4: Outflow traffic from a highway on-ramp vs ratio of minimum headway in the same road to minimum headway in different roads r_{gurad}

ramp road vs time in a simulation. As shown in Fig. 3, the proposed scheme keeps density of vehicles on a main road lower than other schemes at every time in the simulation. This is because the proposed scheme preferentially assigns timing of merging to vehicles on a congested road. Since speed of vehicles becomes high as assigned timing becomes early, the proposed scheme preferentially assigns timing of merging to vehicles on a congested road to maximize average speed of vehicles. By continuously assigning the timing of merging to vehicles on a congested road, the proposed scheme keeps density of vehicles on both the main and ramp road almost the same values at every time in the simulation. On the other hand, density of vehicles on a main road of the previous scheme increases as time in the simulation passes. This is because the previous scheme determines optimal timing of vehicles to decrease frequency of appearance of t_{guard} for minimization of total travel time of vehicles. Since t_{guard} is set to avoid collision of vehicles on different roads, it is general that the value of t_{guard} is larger than the value of t_{head} [14]. Hence, vehicles in the previous scheme make groups among them on the same road to decrease total travel time of vehicles. As a result, the length of the group of vehicles on a ramp road becomes longer and longer at every scheduling of the previous scheme when inflow traffic of a ramp road becomes high. Since vehicles on a main road have to follow a group of vehicles on a ramp road, density of vehicles on a main road is continuously congested when inflow traffic of a ramp road is high. In the FIFO scheme, density of vehicles on both the main and ramp road becomes larger than that of other schemes as time in the simulation passes. This is because the FIFO scheme alternately assigns merging timing to vehicles on both the main and ramp road in order of distance from them to a merging zone. As a result, frequency of appearance of t_{guard} becomes higher than other schemes, and the density of vehicles becomes high on both the main and ramp road.

3.2 Scenario 2

In this scenario, evaluation metrics of each scheme are evaluated by changing r_{guard} from 0.05 to 1.00. In other words, minimum safety headway in the same road changes from 0.2 (sec) to 4.0 (sec). In contrast, the value of r_{main} is fixed to 0.4. This is because the simulation results of the FIFO, previous and proposed scheme are almost the same in the scenario 1 when the value of r_{main} is 0.4.

3.2.1 Outflow Traffic from Highway On-Ramp vs r_{guard}

Figure 4 shows outflow traffic from a highway on-ramp vs ratio of minimum headway in the same road to minimum headway in different roads r_{gurad}. As shown in Fig. 4, the outflow traffic from a highway on-ramp of the proposed scheme and the previous scheme decreases from r_{guard} = 0.65. This is because total inflow traffic exceeds the maximum outflow traffic of a highway on-ramp. The maximum outflow traffic is estimated by following calculation,

$$\text{maximum outflow traffic} \fallingdotseq \frac{3600}{min(t_{head}, t_{guard})}. \tag{5}$$

Specifically, when r_{guard} is 0.65, the maximum outflow traffic of a highway on-ramp is calculated as $3600/(4.0*0.65) \fallingdotseq 1384$. Since the total inflow traffic of both the main and ramp road is 1400 $(veh/hour)$ and exceeds the maximum outflow traffic, the outflow traffic of the proposed scheme and the previous scheme starts to decrease from r_{guard} = 0.65. On the contrast with the proposed scheme and the previous scheme, the outflow traffic of the FIFO scheme is lower than that of the other schemes at every value of r_{guard}. This is because the frequency of appearance of t_{guard} in the FIFO scheme is higher than that in the other schemes. Since t_{guard} is longer than t_{head}, vehicles in the FIFO scheme takes longer time to merge in to a highway on-ramp than vehicles in the other schemes do. As a result, the outflow traffic of the FIFO scheme is lower than that of the other

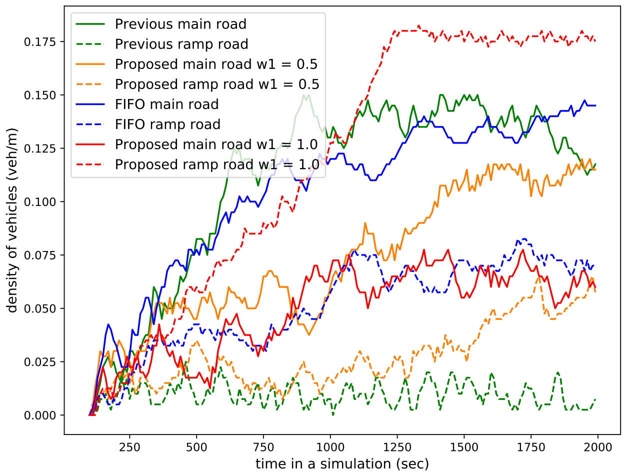

Fig. 5: Density of vehicles on both the main and ramp road vs time in a simulation

schemes at every value of r_{guard}.

3.2.2 Density of Vehicles vs Time in A Simulation

In order to show influence of each scheme on density of vehicles, we fix the value of r_{guard} to 0.8.

Figure 5 shows density of vehicles on both the main and ramp road vs time in a simulation. As shown in Fig. 5, difference between density of vehicles on both the main and ramp road in the proposed scheme with $w_1 = 1.0$ is higher than that in the proposed scheme with $w_1 = 0.5$. This is because the proposed scheme with $w_1 = 1.0$ assigns timing of merging only to vehicles on a main road. In contrast, since the proposed scheme with $w_1 = 0.5$ considers fairness between both the main and ramp road in terms of traffic efficiency, the proposed scheme with $w_1 = 0.5$ decreases the difference of density of vehicles between both the main and ramp road. In addition, the difference between density of vehicles on both the main and ramp road of the proposed scheme with $w_1 = 0.5$ is lower than that of the previous scheme at every time in a simulation. This is because the proposed scheme preferentially assigns timing of merging to vehicles on a congested road. Although difference between density of vehicles on the both main and ramp road of the proposed scheme with $w_1 = 0.5$ is similar with that of the FIFO scheme, the density of vehicles on both the main and ramp road is lower that that of the FIFO scheme at every time in a simulation. Since the frequency of appearance of t_{guard} in the FIFO scheme is higher than that in the other schemes, vehicles takes longer time to merge into a highway on-ramp than vehicles in the other schemes. As a result, the FIFO scheme causes traffic congestion on both the main and ramp road.

4. Conclusion

In this paper, we have shown investigation of a scheduling scheme for cooperative merging at a highway on-ramp with maximizing average speed of automated vehicles. Based on traffic model that density and speed of vehicles have a negative correlation, we formulate the objective function that decreases density of vehicles on whole roads and ensures fairness between both the main and ramp road in terms of traffic efficiency. Simulation result shows that the proposed scheme increases the outflow traffic by 400 (veh/h) at most in comparison with related schemes. Furthermore, simulation result shows that Furthermore, simulation result shows that the proposed scheme decreases difference between density of vehicle on a main road and that of a ramp road by considering fairness between both the main and ramp road in terms of traffic efficiency.

acknowledgment

This work was partly supported by JSPS KAKENHI Grant Numbers JP17K06440, JP20H04180.

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