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A Scheduling Scheme for Autonomous Vehicle Highway Merging With an Outflow Traffic and Fairness Analysis

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ABSTRACT Recently, vehicle-to-infrastructure (V2I) communication-based scheduling schemes for connected and automated vehicles (CAVs) on highway on-ramps have received attention because the schemes assign optimal merging times to CAVs based on their criteria, such as first-in first-out order or minimizing CAV total travel time. However, these schemes cause traffic congestion due to the criteria when the vehicle inflow traffic becomes high. To mitigate traffic congestion, a scheduling scheme should assign merging times to CAVs to decrease road vehicle density. In this paper, we propose a scheduling scheme for autonomous vehicle highway merging with an outflow traffic and fairness analysis. We formulate a multiobjective function that achieves both outflow traffic maximization and fairness in assigned merging times. Since more vehicles pass a highway on-ramp as highway on-ramp outflow traffic increases, the proposed scheme decreases vehicle density on roads by maximizing the outflow traffic. Furthermore, the proposed scheme distributes the vehicle density on both the main and ramp roads by fairly assigning their merging times. Simulation results show that the proposed scheme mitigates the potential traffic congestion of previous scheduling schemes. Furthermore, the proposed scheme improves outflow traffic from highway on-ramps by more than 200 veh/h compared with the previous scheduling schemes.

INDEX TERMS Autonomous vehicles, highway merging, traffic efficiency, fairness in merging times, traffic congestion.

I. INTRODUCTION

Recently, traffic congestion has been regarded as a problem to be solved. 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], which causes aggressive driving behavior and slows the process of recovering smooth traffic flow [3]. One of the sources of traffic congestion is merging onto a highway on-ramp. Since multiple inflow traffic concentrates on highway on-ramps, drivers have to drive carefully. Careful driving decreases vehicle speed and causes traffic congestion [4]. Therefore, highway merging is regarded as a traffic bottleneck [5].

One of the common schemes for mitigating traffic congestion at highway on-ramps is a ramp metering scheme. A ramp metering scheme utilizes a traffic light at a highway on-ramp and regulates vehicles on one road that are merging onto another road. However, this scheme forces vehicles to stop near a highway on-ramp, and vehicles are forced into stop-and-go driving. This movement causes a wave of stop-and-go traffic, which is a reason for traffic congestion [6].

With the development of vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication, connected and automated vehicles (CAVs) have the potential to mitigate traffic congestion and improve traffic efficiency [7]. Since V2V and V2I communication enables CAVs to share when to merge onto a highway on-ramp, they can manipulate their merging times. Hence, V2V and V2I communication-based schemes can avoid undesirable stop-and-go driving. However, since CAVs independently determine their merging times in V2V communication-based schemes, it is difficult to ensure the optimality of road traffic

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efficiency. To achieve optimality, V2I communication-based schemes are considered. In V2I communication-based schemes, a central control server collects road vehicle information and schedules optimal merging times. Although V2I communication-based schemes optimize merging times based on their criteria, they do not optimize merging times in terms of outflow traffic from a highway on-ramp. Therefore, there is room to improve highway on-ramp traffic efficiency. Furthermore, V2I communication-based schemes cannot fairly assign merging times to vehicles on both the main and ramp roads when inflow traffic becomes high. In other words, these schemes may only assign vehicle merging times on a road to achieve their optimality. As a result, V2I communication-based schemes cause traffic congestion on another road.

In this paper, we propose a scheduling scheme for autonomous vehicle highway merging with an outflow traffic and fairness analysis. To mitigate the traffic congestion of the V2I communication-based schemes, the proposed scheduling scheme takes two approaches. One approach is the maximization of outflow traffic from a highway on-ramp by assigning optimal merging times to vehicles. The other approach is the distribution of traffic congestion on roads by fairly assigning merging times to vehicles on different roads. To assign such merging times, we analyze the relation among highway on-ramp outflow traffic, merging time fairness, and merging times. Based on the analysis, we formulate an objective function that achieves both the outflow traffic maximization and fairness in merging times.

The contributions of this paper are as follows:

- We propose a scheduling scheme that achieves both outflow traffic maximization and fairness in merging times to mitigate the potential traffic congestion of previous schemes.
- Simulation results show that the proposed scheduling scheme improves highway on-ramp outflow traffic and fairly assigns merging times to vehicles.
- In two traffic scenarios, we confirmed that the proposed scheme mitigates the potential traffic congestion of the previous schemes by achieving both outflow traffic maximization and fairness in merging times in simulation results.

The rest of this paper is organized as follows: Section 2 reviews related work. Section 3 presents the proposed scheme. Section 4 shows the evaluation results. Section 5 concludes this paper.

II. RELATED WORK

To mitigate traffic congestion and improve traffic efficiency, several schemes for coordinating vehicle highway on-ramp merging have been proposed. These schemes are classified into three types as follows: (1) ramp metering schemes, (2) decentralized coordination schemes and (3) centralized scheduling schemes. The representative schemes are explained in the following.

A. RAMP METERING SCHEMES

Ramp metering schemes utilized a traffic light at a highway on-ramp and regulated vehicles on one road merging onto another road. Specifically, ramp metering schemes switched red and green traffic light signals and coordinated vehicles at a highway on-ramp [8]. The challenging task of ramp metering schemes was to determine when to switch traffic light signals to maintain vehicle density for traffic efficiency. To achieve traffic efficiency at one highway on-ramp, Hadj-Salem *et al.* proposed a local feedback control-based scheme [9]. They formulated causal dependence between inflow traffic and outflow traffic as a feedback control and maintained the vehicle density near a highway on-ramp. However, this scheme could not maintain the optimal vehicle density over time because this scheme only considers the current vehicle. To achieve the optimal vehicle density over time, Bellemans *et al.* proposed a model predictive control (MPC)-based scheme [10]. In the MPC-based scheme, the vehicle density in the future was predicted by a traffic model. Specifically, the vehicle density at some time steps was predicted, and the total vehicle density was minimized. However, computational complexity quickly increased with the number of control inputs [11]. To overcome the computational complexity, Fares *et al.* proposed a Q-learning-based scheme [12]. Q-learning is an algorithm for learning optimal actions under circumstances by rewards [13]. In the Q-learning-based scheme, the difference between the vehicle density in time steps and the theoretic optimal vehicle density is applied as a reward, and the timing to switch a traffic light with a high reward is selected as an optimal action.

Although ramp metering schemes can maintain vehicle density for traffic efficiency, regulating vehicles on a road merging onto another road forces them to stop near a highway on-ramp, and they are forced into stop-and-go driving. This movement causes a wave of stop-and-go traffic, which is a reason for traffic congestion.

B. DECENTRALIZED COORDINATION SCHEMES

With the development of V2V communication, several decentralized coordination schemes have been proposed. In decentralized coordination schemes, each vehicle determines its own merging time onto a highway on-ramp and manipulates its speed based on information that is sent from the other vehicles through V2V communication. If the coordination of decentralized coordination schemes succeeds, vehicles on a road do not have to wait for vehicles on another road to merge onto a highway on-ramp. Therefore, decentralized coordination schemes can avoid undesirable stop-and-go driving conditions. The challenging task of decentralized coordination schemes was how to manipulate vehicles to ensure safety and improve traffic efficiency through V2V communication. Milanes *et al.* proposed a virtual vehicle-based scheme to ensure sufficient distance for merging onto a highway on-ramp [14]. In this scheme, the vehicle positions on a road are mapped onto another road, and the safe distance between vehicles on both roads is ensured. However, since humans drive their vehicles according to several traffic conditions, it is not natural for human drivers to focus only on the distance between vehicles. To achieve natural vehicle manipulation, Hou *et al.* proposed a real traffic data-driven manipulation scheme [15]. They focused on five features that included the distance between vehicles to manipulate them based on fuzzy control. Furthermore, to determine the importance of each feature in fuzzy control, they utilized decision trees through real traffic data.

Although decentralized coordination schemes achieved smooth traffic without undesirable stop-and-go driving, these schemes have difficulty achieving traffic efficiency optimality because the vehicles independently determine their merging times.

C. CENTRALIZED SCHEDULING SCHEMES

To overcome the difficulty in decentralized coordination schemes, centralized scheduling schemes was proposed. Centralized scheduling schemes utilized a central control server to calculate the optimal vehicle merging times at a highway on-ramp. In detail, a central control server collects information of vehicles through V2I communication and calculates their optimal merging times on both the main and ramp roads. Centralized scheduling schemes are classified into the first-in first-out (FIFO)-based scheduling scheme [16] and the optimization-based scheduling scheme [17], [18]. Rios-Torres *et al.* proposed a FIFO-based scheduling scheme that minimizes the total vehicle acceleration for smooth traffic flow [16]. In this scheme, vehicles alternatively merge onto a highway on-ramp in order of the distance between them to a highway on-ramp. However, the safe headway time to avoid vehicle collisions on different roads increases as inflow traffic becomes high. As a result, vehicles take additional time to merge onto a highway on-ramp, and traffic congestion occurs on roads. To mitigate traffic congestion, optimization-based scheduling schemes that minimize the total vehicle travel time were proposed. Specifically, Awal *et al.* formulated a scheduling problem with a nonlinear formulation [17], and Ding *et al.* converted the formulation into a mixed-integer linear formulation by utilizing a big-M method [18]. The main idea of these scheduling schemes is that they create vehicle groups on the same road to decrease the vehicle safe headway time on different roads. Since the vehicle safe headway time on different roads is set longer than that on the same road to avoid vehicle collisions [19], the scheme creates groups of vehicles on the same road by minimizing their total travel time. However, the length of groups of vehicles on a road becomes too long as inflow traffic becomes high. Since vehicles on another road have to wait for the groups to pass a highway on-ramp, traffic congestion occurs on the other road.

D. MOTIVATION OF THIS PAPER

To summarize the shortcomings of the previous centralized scheduling schemes, the FIFO-based scheme causes traffic congestion on roads, and the optimization-based scheduling scheme causes traffic congestion on one road when inflow traffic becomes high. For mitigating the potential traffic congestion of the previous centralized scheduling schemes, we can take two approaches. One approach is the maximization of outflow traffic from a highway on-ramp. Although several optimization-based schemes were proposed for the traffic efficiency improvement, these schemes did not optimize merging times in terms of the outflow traffic. In our previous work, we proposed a scheduling scheme that maximizes outflow traffic from highway on-ramps to improve the traffic efficiency [20]. This scheme, however, assigns merging times to vehicles only on one road for the outflow traffic maximization. As a result, this scheme causes traffic congestion on the other road similar to the previous optimization-based schemes. The other approach is the distribution of traffic congestion on roads by fairly assigning merging times to vehicles on different roads. Although the FIFO-based scheduling scheme fairly assigns merging times in the order of distance from the vehicle to the highway on-ramp, this scheme cannot assign optimal merging times in terms of the outflow traffic from a highway on-ramp.

Motivated by the above, we argue that it is necessary to schedule vehicle merging times such that both the outflow traffic maximization and fairness in assigned merging times are achieved. Furthermore, it is necessary to know when to attach importance to outflow traffic maximization or fairness in assigned merging times in several traffic scenarios.

III. PROPOSED SCHEME

In this paper, we propose a scheduling scheme for autonomous vehicle highway merging with an outflow traffic and fairness analysis. To assign merging times to vehicles such that traffic congestion on roads is mitigated, we formulate a multiobjective function that achieves both outflow traffic maximization from a highway on-ramp and the fairness of the assigned vehicle merging times on roads. The outflow maximization decreases vehicle density on roads, and the fairness of assigned vehicle merging times distributes vehicle density on roads. As a result, the proposed scheme can mitigate the traffic congestion flexibly by changing importance to both the outflow traffic maximization and the fairness in assigned merging times on roads. Therefore, the proposed scheme mitigates the traffic congestion on roads even if inflow traffic becomes high.

First, we explain the system model of the proposed scheme in subsection III-A. Then, we formulate several constraints for assigning feasible merging times to vehicles in subsection III-B. Next, we formulate the proposed objective function, which achieves both outflow traffic maximization and fairness in assigned merging times in subsection III-C. Finally, we present the scheduling algorithm in subsection III-D.

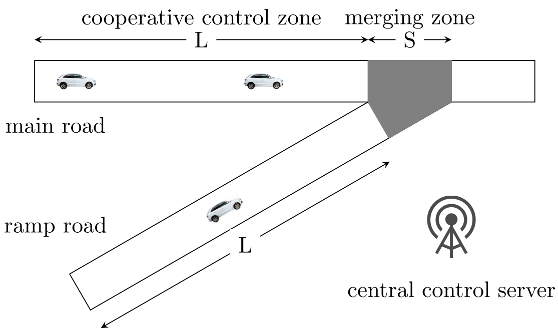


FIGURE 1. **A common scenario for vehicles merging onto a highway on-ramp.**

A. SYSTEM MODEL

Fig. 1 shows a common scenario for vehicles merging onto a highway on-ramp. The scenario consists of vehicles and a central control server. All vehicles are assumed to be autonomous, and they are equipped with onboard units (OBUs) that can communicate with the central control server. In addition, the central control server can control vehicles inside a cooperative control zone. When vehicles enter the cooperative control zone, they begin sending their information to the central control server. For example, vehicle i, V_i, sends information that includes distance from V_i to a merging zone d_i, maximum speed v^i_{max}, minimum speed v^i_{min}, maximum acceleration a^i_{max}, minimum acceleration a^i_{min}, and current speed v^i_{now}. By using this information, the server calculates the optimal vehicle merging times at regular intervals. After the calculation, the server sends the merging times to the vehicles. Vehicles that receive the merging times manipulate their speeds to reach the merging zone at their merging time. Specifically, when the distance between a vehicle and the vehicles ahead is less than the safe following distance, the vehicle follows those distances. Otherwise, the vehicle runs freely.

B. CONSTRAINTS FOR THE SCHEDULING PROBLEM

A central control server calculates the assigned merging time t^i_{assign} of V_i at regular intervals. To achieve feasible merging times, several constraints are introduced.

To avoid overlap of assigned times between vehicles on the same road, the constraint between vehicle V_i and vehicle V_{i-1} on the same road is formulated as

$$t_{head} \leq t^i_{assign} - t^{i-1}_{assign}, \qquad d_{i-1} \leq d_i, \tag{1}$$

where t_{head} denotes the minimum safe headway time for the same road. To avoid vehicle collision on different roads, the constraint between vehicle V_j and vehicle V_k on different roads is formulated as

$$\begin{aligned} &t_{guard} \leq t^j_{assign} - t^k_{assign}, \\ &\text{OR} \\ &t_{guard} \leq t^k_{assign} - t^j_{assign}, \end{aligned} \tag{2}$$

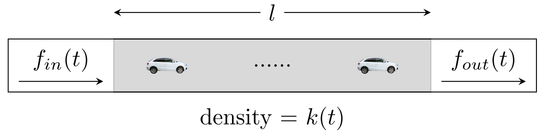


FIGURE 2. **Relation between inflow traffic, outflow traffic, and vehicle density on a road segment with length *l*.**

where t_{guard} denotes the minimum safe headway time on different roads. Let t^i_{min} and t^i_{max} denote the lower bound of the reachable time and the upper bound of the reachable time for V_i. The reachable time constraing of V_i is formulated as

$$t^i_{min} \leq t^i_{assign} \leq t^i_{max}. \tag{3}$$

Specifically, V_i takes at minimum time, which is the sum of both the time to accelerate with a^i_{max} and the time to run at v^i_{max}. Similarly, V_i takes at the maximum time that is the sum of both the time to decelerate with a^i_{min} and the time to run at v^i_{min}. Therefore, t^i_{min} and t^i_{max} are calculated as

$$t^i_{min} = t_{now} + \frac{v^i_{max} - v^i_{now}}{a^i_{max}} + \frac{(d_i - d^i_{acc})}{v^i_{max}}, \quad d^i_{acc} \leq d_i, \tag{4}$$

$$t^i_{max} = t_{now} + \frac{v^i_{min} - v^i_{now}}{a^i_{min}} + \frac{(d_i - d^i_{dec})}{v^i_{min}}, \quad d^i_{dec} \leq d_i, \tag{5}$$

where t_{now}, d^i_{acc}, and d^i_{dec} denote the current time, distance to accelerate to v^i_{max}, and distance to decelerate to v^i_{min}. Specifically, it is known that d^i_{acc} and d^i_{dec} are calculated as $\frac{(v^i_{max})^2-(v^i_{now})^2}{2a^i_{max}}$ and $\frac{(v^i_{min})^2-(v^i_{now})^2}{2a^i_{min}}$. When d_i is less than d^i_{acc} or d^i_{dec}, V_i merges onto the highway on-ramp by accelerating or decelerating. Then, t^i_{min} and t^i_{max} are calculated by solving the following equation:

$$d_i = v^i_{now}(t^i_{assign} - t^i_{now}) + a^i(t^i_{assign} - t^i_{now})^2, \tag{6}$$

where a^i denotes the acceleration of V_i. Equation (6) denotes that V_i runs distance d_i with acceleration a^i and initial speed v^i_{now}. Since t^i_{assign} is minimized when a^i is a^i_{max} and maximized when a^i is a^i_{min}, t^i_{min} and t^i_{max} are calculated as

$$t^i_{min} = t_{now} + \frac{-v^i_{now} + \sqrt{(v^i_{now})^2 + 4a^i_{max}d_i}}{2a^i_{max}}, \quad d_i < d^i_{acc}, \tag{7}$$

$$t^i_{max} = t_{now} + \frac{-v^i_{now} + \sqrt{(v^i_{now})^2 + 4a^i_{min}d_i}}{2a^i_{min}}, \quad d_i < d^i_{dec}. \tag{8}$$

C. BACKGROUND AND PROPOSED OBJECTIVE FUNCTION

A central control server calculates t^i_{assign} that maximizes the proposed objective function. In this section, we introduce the proposed objective function with an analysis of outflow traffic and fairness. For simplicity, we first analyze them with one road. Then, we explain them with both the main and ramp roads. Finally, the proposed objective function is formulated.

1) RELATION BETWEEN INFLOW TRAFFIC, OUTFLOW TRAFFIC, AND VEHICLE DENSITY ON A ROAD SEGMENT

Fig. 2 shows relation between inflow traffic, outflow traffic, and vehicle density on a road segment with length l. Inflow traffic is expressed as the number of vehicles that enter the segment per unit time, and outflow traffic is expressed as the number of vehicles that exit the segment per unit time. Specifically, $f_{in}(t)$, $f_{out}(t)$, and $k(t)$ denote inflow traffic at time t, outflow traffic at time t, and vehicle density at time t on a road segment, respectively. The relation among these values is as follows:

$$\int_0^t f_{in}(t')dt' - \int_0^t f_{out}(t')dt' = lk(t). \tag{9}$$

Equation (9) denotes that the number of vehicles on the road segment is equal to the value of the number of vehicles entering the segment minus the number of vehicles exiting the segment until time t. When the purpose of the proposed scheme is to improve the outflow traffic from the road segment, the objective function F is expressed as follows:

$$F = \int_0^t f_{in}(t')dt' - lk(t). \tag{10}$$

As shown in (10), the outflow traffic increases according to a decrease in the vehicle density. To decrease the vehicle density, we utilize the relation between vehicle density and vehicle speed. Specifically, it has been indicated that the vehicle density and vehicle speed have a negative correlation in existing traffic models [21]. To utilize the negative correlation simply, we utilize Greenshield traffic model, which is the simplest one in the existing traffic models [22]. Based on the Greenshield traffic model, the vehicle density k is expressed as follows:

$$k = -\alpha v_{ave} + \beta, \quad \alpha = \frac{k_{max}}{v_{max}}, \quad \beta = k_{max}, \tag{11}$$

where v_{ave}, v_{max}, k_{max} denote average vehicle speed, maximum vehicle speed, and maximum vehicle density on the road segment, respectively. By substituting (11), (10) is converted as follows:

$$F = \int_0^t f_{in}(t')dt' + l(\alpha v_{ave}(t) - \beta), \tag{12}$$

where $v_{ave}(t)$ denotes average vehicle speed on the road segment at time t. In the next subsection III-C2, we analyze the relation between inflow traffic, outflow traffic, and vehicle density on both the main and ramp roads in the same way with (9), (10), (11), and (12).

2) RELATION BETWEEN INFLOW TRAFFIC, OUTFLOW TRAFFIC, AND VEHICLE DENSITY ON BOTH THE MAIN AND RAMP ROADS

Fig. 3 shows the relation between inflow traffic, outflow traffic, and vehicle density on both the main and ramp roads.

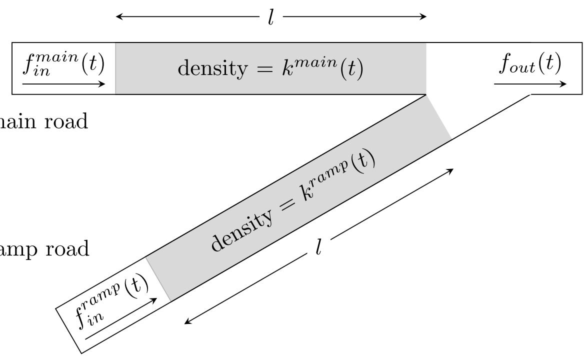


FIGURE 3. Relation between inflow traffic, outflow traffic, and vehicle density on both the main and ramp roads.

In the same way with (9), the relation on both the main and ramp roads is formulated as follows:

$$\left(\int_0^t f_{in}^{main}(t')dt' + \int_0^t f_{in}^{ramp}(t')dt'\right) - \int_0^t f_{out}(t')dt' = lk^{main}(t) + lk^{ramp}(t), \tag{13}$$

where $f_{in}^{main}(t)$, $f_{in}^{ramp}(t)$, $k^{main}(t)$, and $k^{ramp}(t)$ denote inflow traffic of a main road, that of a ramp road, density on a main road, and that on a ramp road at time t, respectively. In the same way with (10), when the purpose of the proposed scheme is to improve the outflow traffic from the highway on-ramp, the objective function F can be formulated as follows:

$$F = \int_0^t f_{in}^{main}(t')dt' - lk^{main}(t) + \int_0^t f_{in}^{ramp}(t')dt' - lk^{ramp}(t). \tag{14}$$

Furthermore, based on the Greenshield traffic model described by (11), (14) can be converted as follows:

$$F = \int_0^t f_{in}^{main}(t')dt' + l(\alpha^{main} v_{ave}^{main}(t) - \beta^{main}) + \int_0^t f_{in}^{ramp}(t')dt' + l(\alpha^{ramp} v_{ave}^{ramp}(t) - \beta^{ramp}), \tag{15}$$

where $v_{ave}^{main}(t)$ and $v_{ave}^{ramp}(t)$ denote average vehicle speed on the main road and that on the ramp road, and α^{main}, β^{main}, α^{ramp}, and β^{ramp} denote constant values of both the main and ramp roads, respectively. According to (11), α^{main} and α^{ramp} have the same value in case that v_{max} and k_{max} for the main road are equal to those for the ramp road, and β^{main} and β^{ramp} also have the same value. Therefore, to simply express (15), we express α^{main} and α^{ramp} as α, and we also express β^{main} and β^{ramp} as β. Here, (15) can be converted as follows:

$$F = l\alpha(v_{ave}^{main}(t) + v_{ave}^{ramp}(t)) + \int_0^t (f_{in}^{main}(t') + f_{in}^{ramp}(t'))dt' - 2l\beta. \tag{16}$$

Since $f_{in}^{main}(t)$, $f_{in}^{ramp}(t)$, l, α and β are independent of both $v_{ave}^{main}(t)$ and $v_{ave}^{ramp}(t)$ in (16), the following proposition is true.

$$\text{maximize} \quad v_{ave}^{main}(t) + v_{ave}^{ramp}(t) \quad \Rightarrow \quad \text{maximize} \quad F. \quad (17)$$

Therefore, we focus on the average vehicle speed on both the main and ramp roads to improve the outflow traffic. In the next subsection III-C3, we formulate the proposed objective function based on Proposition (17).

3) PROPOSED OBJECTIVE FUNCTION

When a central control server assigns vehicle i with merging time t_{assign}^{i} at time t, $v_{ave}^{main}(t)$ and $v_{ave}^{ramp}(t)$ are calculated as follows:

$$v_{ave}^{main}(t) = \frac{1}{|V_{main}|} \sum_{i \in V_{main}} \frac{d_i}{t_{assign}^{i} - t_{now}}, \quad (18)$$

$$v_{ave}^{ramp}(t) = \frac{1}{|V_{ramp}|} \sum_{j \in V_{ramp}} \frac{d_j}{t_{assign}^{j} - t_{now}}, \quad (19)$$

where V_{main}, V_{ramp}, d_i and t_{now} denote a set of vehicles on a main road, that on a ramp road, distance from vehicle i to a merging zone, and current time, respectively. Furthermore, to decrease vehicle density on both the main and ramp roads effectively, we add weights proportion to the number of vehicles on each road to $v_{ave}^{main}(t)$ and $v_{ave}^{ramp}(t)$. Here, based on Proposition (17), the objective function F_1 is formulated as follows:

$$\begin{aligned} F_1 &= \frac{|V_{main}|}{|V|} v_{ave}^{main}(t) + \frac{|V_{ramp}|}{|V|} v_{ave}^{ramp}(t) \\ &= \frac{|V_{main}|}{|V|} \frac{1}{|V_{main}|} \sum_{i \in V_{main}} \frac{d_i}{t_{assign}^{i} - t_{now}} \\ &\quad + \frac{|V_{ramp}|}{|V|} \frac{1}{|V_{ramp}|} \sum_{j \in V_{ramp}} \frac{d_j}{t_{assign}^{j} - t_{now}} \\ &= \frac{1}{|V|} \sum_{k \in V} \frac{d_i}{t_{assign}^{i} - t_{now}}, \quad (20) \\ V &= \{V_{main}, V_{ramp}\}. \end{aligned}$$

Specifically, the objective function F_1 denotes the average vehicle speed on both the main and ramp roads.

Although the objective function F_1 ensures outflow traffic maximization on roads, it does not ensure fairness of the assigned vehicle merging times on both the main and ramp roads. In other words, it is possible that maximization of F_1 may preferentially assign merging times to vehicles only on one road. To fairly assign merging times to vehicles on both the main and ramp roads, we focus on the difference between the average vehicle speed on the main road and that on the ramp road. Since the difference in the average vehicle speed increases as the vehicle merging time on one road is delayed, the proposed scheme assigns merging times to vehicles such that the difference between the average vehicle speed on the main road and that on a ramp road is minimized. Here, the objective function F_2, which considers the fairness of the assigned vehicle merging times on both the main and ramp roads is expressed as

$$F_2 = \left| v_{ave}^{main}(t) - v_{ave}^{ramp}(t) \right|. \quad (21)$$

Finally, the objective function F, which considers both the outflow traffic maximization and fairness in assigned merging times is expressed as

$$\begin{aligned} F &= w_1 F_1 - (1 - w_1) F_2, \\ 0 &\leqq w_1 \leqq 1, \end{aligned} \quad (22)$$

where w_1 denotes the weight of F_1. When w_1 is 1.0, F_1 is maximized by maximizing F, and outflow traffic from a highway on-ramp is maximized. When w_1 is 0.0, F_2 is minimized by maximizing F, and the fairness in the assigned vehicle merging times on both the main and ramp roads is achieved.

D. SCHEDULING ALGORITHM

A central control server seeks the optimal vehicle merging times that maximize the proposed objective function (22) with constraints (1), (2) and (3) based on a brute-force search. The scheduling algorithm consists of four phases: (1) seeking all vehicle sequence patterns, (2) calculating values of the objective function for all the sequence patterns, (3) selecting the optimal vehicle sequence and optimal merging times, and (4) validating the optimal merging times.

1) SEEKING ALL VEHICLE SEQUENCE PATTERNS

First, the algorithm seeks all vehicle sequence patterns based on a brute-force search. A vehicle sequence means an order of vehicle merging onto a highway on-ramp. Let V_{main} and V_{ramp} denote a set of vehicles on a main road, that on a ramp road, respectively. Then, a vehicle sequence on a main road and that on a ramp road are expressed as $\{V_1, \ldots, V_{|V_{main}|}\}$ and $\{V_1, \ldots, V_{|V_{ramp}|}\}$, and one of all the vehicle sequence patterns is expressed as $\{V_1, \ldots, V_{|V_{main}|+|V_{ramp}|}\}$. The number of all vehicle sequence patterns is calculated as ${}_{|V_{main}|+|V_{ramp}|}\mathrm{C}_{|V_{main}|}$. Therefore, the computational complexity of the scheduling algorithm exponentially increases as $|V_{main}| + |V_{ramp}|$ increases. To decrease the computational complexity, the algorithm groups vehicles on the main road and ramp road by each road segment. Let L and l_{seg} denote the length of a cooperative control zone and the length of the road segment. Then, the number of vehicle groups on each road is calculated as $\lceil \frac{L}{l_{seq}} \rceil$. Therefore, when G^{main} and G^{ramp} denote a vehicle sequence in a vehicle group on a main road and that on a ramp road respectively, a vehicle sequence on the main road and that on the ramp road are expressed as $\{G_1^{main}, \ldots, G_{\lceil \frac{L}{l_{seq}} \rceil}^{main}\}$ and $\{G_1^{ramp}, \ldots, G_{\lceil \frac{L}{l_{seq}} \rceil}^{ramp}\}$. Then, the number of all vehicle sequence patterns is calculated as ${}_{\lceil \frac{L}{l_{seq}} \rceil + \lceil \frac{L}{l_{lseq}} \rceil}\mathrm{C}_{\lceil \frac{L}{l_{lseq}} \rceil}$. In addition to all the vehicle sequence patterns, we add a sequence in which vehicles are in order of distance from them to a merging zone to the sequences. This sequence is the same as a sequence of FIFO-based scheduling schemes. Hence, the sequence will fairly assign merging times to vehicles on both the main and ramp roads.

2) CALCULATING VALUES OF THE OBJECTIVE FUNCTION FOR ALL THE SEQUENCE PATTERNS

After seeking all the vehicle sequence patterns, the algorithm calculates values of the objective function for all the sequences. Let one of the vehicle sequences be denoted as $\{V_1, \ldots, V_{|V_{main}|+|V_{ramp}|}\}$. The assigned merging time t^i_{assign} is calculated as follows:

$$t^i_{assign} = \begin{cases} max(t^i_{min}, t^{i-1}_{assign} + t_{safety}) & (2 \leq i) \\ t^i_{min} & (i = 1), \end{cases} \tag{23}$$

$$t_{safety} = \begin{cases} t_{head} \ (V_i \text{ and } V_{i-1} \text{ are on the same road}) \\ t_{guard} \text{ (otherwise).} \end{cases} \tag{24}$$

Equation (23) is equivalent to constraints (1) and (2). By substituting t^i_{assign} of the sequence into the proposed objective function (22), the algorithm calculates the values of the objective function for the sequence.

3) SELECTING THE OPTIMAL VEHICLE SEQUENCE AND OPTIMAL MERGING TIMES

After calculating the values of the objective function for all the sequences, the algorithm selects the optimal sequence and optimal merging time that maximizes the objective function from all the sequences.

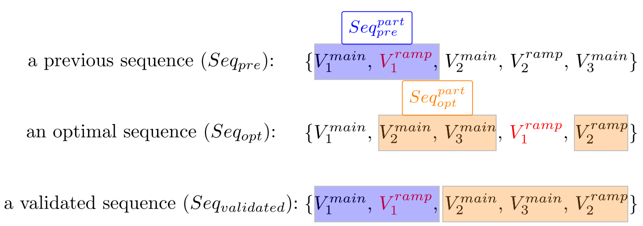


FIGURE 4. Example of the validated sequence of vehicles.

4) VALIDATING THE OPTIMAL MERGING TIMES

A case exists in which the optimal sequence and optimal merging time are infeasible solutions because the optimal merging time may not satisfy the constraint (3). In this case, the algorithm creates a validated sequence of vehicles $Seq_{validated}$ that satisfies the constraint (3). Specifically, if a previous sequence Seq_{pre} changes to an optimal sequence Seq_{opt} such that merging time does not satisfy the constraint, the validation algorithm utilizes a part of Seq_{pre} instead of Seq_{opt} to create $Seq_{validated}$. Fig. 4 shows the example of the validated sequence of vehicles. First, the algorithm seeks the last vehicle whose newly assigned merging time does not satisfy constraint (3) from Seq_{pre}. In Fig. 4, a vehicle sequence is changed from Seq_{pre} to Seq_{opt}, and the newly assigned merging time of V^{ramp}_1 does not satisfy constraint (3). Therefore, V^{ramp}_1 becomes the last vehicle in Seq_{pre}. Then, Seq^{part}_{pre} is composed of vehicles that exist between a head vehicle and the last vehicle in Seq_{pre}. Furthermore, Seq^{part}_{opt} is created by excluding vehicles in Seq^{part}_{pre} from Seq_{opt}. Finally, $Seq_{validated}$ is created by connecting Seq^{part}_{prior} and Seq^{part}_{opt} in this order. The assigned vehicle merging times is newly calculated by using $Seq_{validated}$ and (23).

IV. EVALUATION

The proposed scheme (proposed) is compared with the FIFO-based scheme (FIFO) [16] and Ding's optimization scheme (previous) [18]. The FIFO-based scheme assigns merging times to vehicles in order of distance from the vehicle to a merging zone. The previous scheme assigns merging times to vehicles such that their total travel time is minimized. All simulations were carried out by using Simulation of Urban MObility (SUMO), which is an open-source microtraffic simulator [23]. In SUMO, vehicles move based on the Krauss car following model, which is a widely used car following model with small vehicle speed errors [24]. The calculation module was implemented in Python 2.7. The calculation was performed on a computer with an Intel Core i7, 3.1 GHz processor and 16 GB memory. In addition, the calculation of the FIFO and previous scheme was performed by using CBC, which is a solver for linear optimization [25]. The major simulation parameters are presented in Table 1. Vehicles enter both the main and ramp roads at random times. A central control server calculates t^i_{assign} of all vehicles every 1 second in SUMO. The number of lanes of both the main and ramp roads is 1. The inflow traffic of a ramp road f^{ramp}_{in} is calculated as $f^{main}_{in} \cdot r_{main}$. The minimum safe headway time on the same road t_{head} is calculated as $t_{guard} \cdot r_{guard}$.

TABLE 1. 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 the main road (r_{main})	[0.0, 1.0]
inflow traffic of the main road (f^{main}_{in})	1,000 veh/h
ratio of minimum headway time on the same road to minimum headway time on different roads (r_{guard})	[0.0, 1.0]
minimum safe headway time on different roads (t_{guard})	4 sec
a segment of a road (l_{seq})	100 m
simulation time ($T_{simulation}$)	2,000 sec

In this evaluation, we use two scenarios, which are as follows:

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

In these scenarios, we evaluate outflow traffic from a highway on-ramp, the average vehicle travel times, and the vehicle density on both the main and ramp roads. The outflow traffic is measured by counting the number of vehicles that have passed a highway on-ramp during the simulation. The vehicle travel time is the elapsed time from when the vehicle comes into a cooperative control zone when the vehicle passes a highway on-ramp. The vehicle density is calculated by dividing the number of vehicles on a road by the length of the road. Finally, we evaluate the calculation time of each scheduling scheme. We simulate 20 times at every value of r_{main} and r_{guard}, and average values of these evaluation metrics are plotted in the simulation results. These evaluation metrics are desired to meet the following requirements:

- the outflow traffic from a highway on-ramp should be high,
- the average vehicle travel time on both the main and ramp roads should be the same and should be low,
- the vehicle density on both the main and ramp roads should be the same and should be low,
- the calculation time should be low.

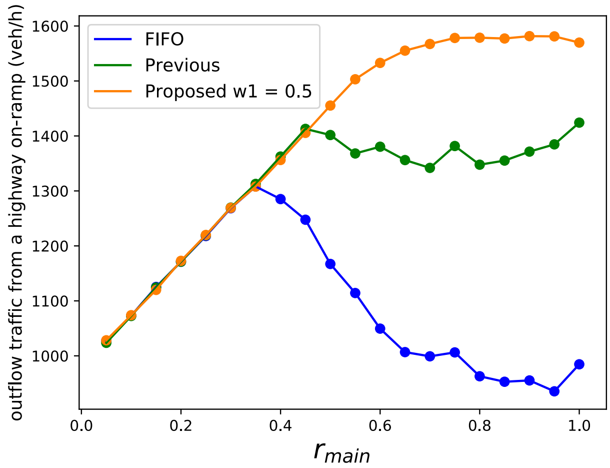
A. SCENARIO 1

In this scenario, we changed r_{main} from 0.0 to 1.0. The minimum safe headway time on the same road t_{head} was fixed to 1 second, which was sufficient minimum headway time for autonomous vehicles [26], [27].

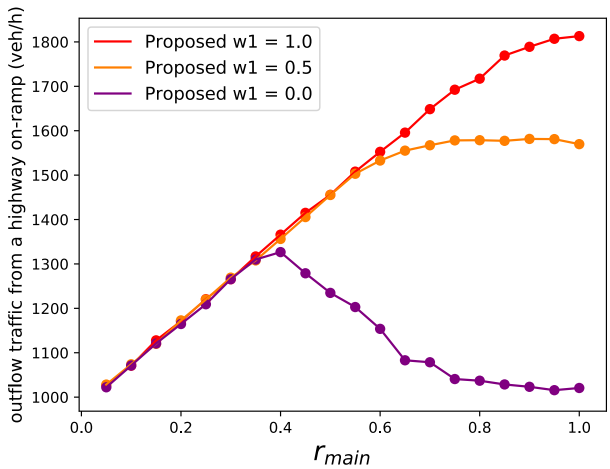
1) OUTFLOW TRAFFIC FROM A HIGHWAY ON-RAMP VS r_{main}

In Fig. 5, we show a comparison among the FIFO, previous, and proposed schemes in terms of outflow traffic. The proposed scheme improves the outflow traffic by approximately 200 veh/h compared with the previous scheme when r_{main} is high. This is because the proposed scheme assigns optimal merging times to vehicles for improvement of the outflow traffic. In contrast, with the proposed scheme, the outflow traffic of the previous scheme is lower than that of the proposed scheme. This is because the previous scheme makes a group of vehicles on a ramp road to minimize their total travel time. As a result, the length of vehicle groups on a ramp road becomes long as r_{main} becomes high. Since vehicles on the main road have to wait for the group of vehicles on the ramp road to pass the highway on-ramp, the vehicle merging times on the main road is delayed. This delay prevents vehicles on the main road from smoothly merging onto a highway on-ramp. The outflow traffic of the FIFO scheme decreases as r_{main} increases. This is because the minimum safe headway time on different roads t_{guard} increases as the inflow traffic of a ramp road increases. Since the opportunity for vehicles on both the main and ramp roads to alternately merge onto a highway on-ramp increases as inflow traffic of the ramp road increases, the minimum safe headway time on different roads t_{guard} increases. As a result, the outflow traffic of the FIFO scheme decreases as r_{main} becomes high.

As shown in Fig. 5(b), when r_{main} is high, the outflow traffic of the proposed scheme increases as the value of w_1 increases. This is because the proposed scheme ensures the optimality of the outflow traffic as the value of w_1 increases. When the value of w_1 is 0.0, the outflow traffic of the proposed scheme decreases as r_{main} increases. This is because the proposed scheme fairly assigns merging times to vehicles on both the main and ramp roads. As a result, the frequency



(a) Comparison between FIFO, previous, and proposed with $w_1 = 0.5$



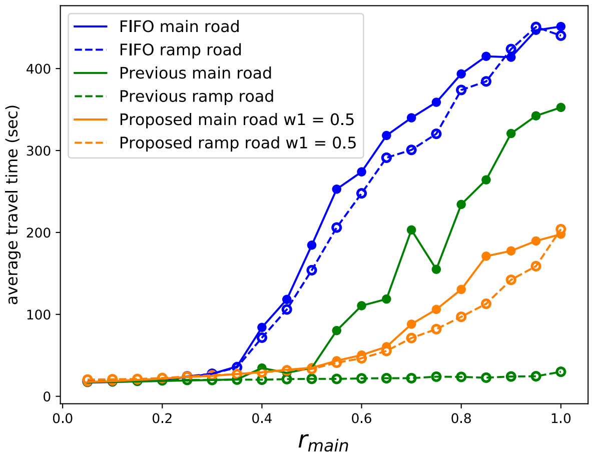
(b) Comparison among proposed schemes with different values of w_1

FIGURE 5. Outflow traffic from a highway on-ramp VS ratio of inflow traffic of ramp road to inflow traffic of the main road, r_{main}.

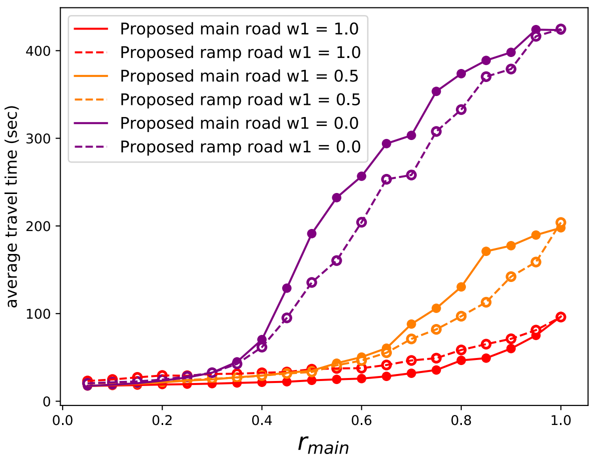
of t_{guard} increases as r_{main} becomes high. Hence, when the value of w_1 is 0.0, outflow traffic from a highway on-ramp decreases as well as the FIFO scheme.

2) AVERAGE TRAVEL TIME OF VEHICLES VS r_{main}

To show the fairness in the assigned merging times, we evaluate the average vehicle travel time on both the main and ramp roads in Fig. 6. The proposed scheme and the FIFO scheme maintain the average travel time of vehicles on both the main and ramp roads almost the same at every value of r_{main}. This result indicates that these schemes can fairly assign merging times to vehicles on both the main and ramp roads. Furthermore, the proposed scheme decreases the average travel time of both the main and ramp roads by more than half of the FIFO scheme as r_{main} becomes high. This is because the proposed scheme decreases the safe headway time on different roads t_{guard} by changing the order of vehicle merging times. As a result, the average travel time of the



(a) Comparison between FIFO, previous, and proposed with $w_1 = 0.5$

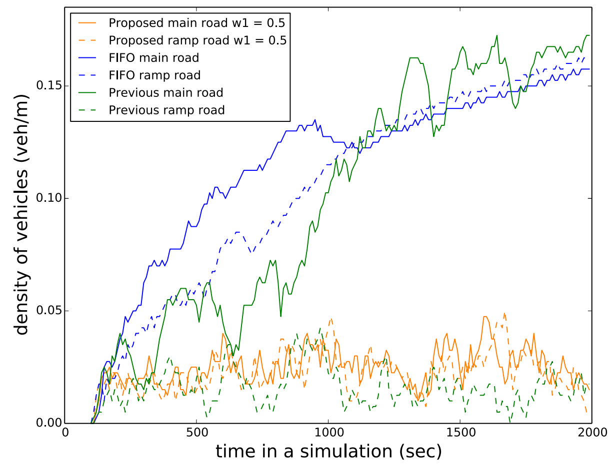


(b) Comparison among proposed schemes with different values of w_1

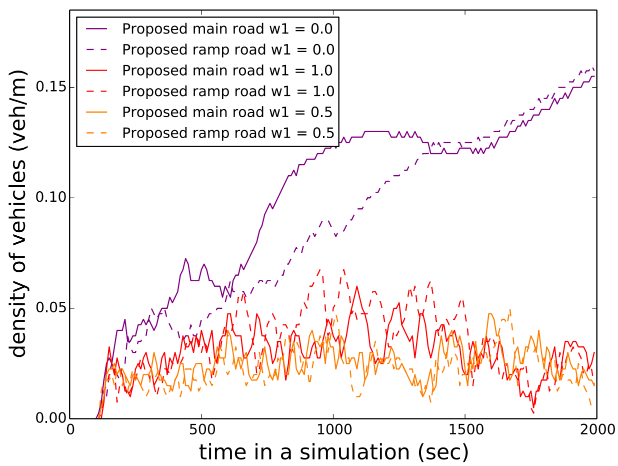
FIGURE 6. Average travel time VS ratio of inflow traffic of ramp road to inflow traffic of the main road, r_{main}.

proposed scheme becomes shorter than that of the FIFO scheme. Although the previous scheme also changes the order of the vehicle merging times by minimizing the total vehicle travel times, the difference in the average travel time of both the main and ramp roads becomes large as r_{main} becomes high. This is because the previous scheme does not consider the fairness of the assigned vehicle merging times on both the main and ramp roads. As a result, the previous scheme tends to assign vehicle merging times vehicles only on a road to minimize their total travel time when r_{main} is high.

As shown in Fig. 6(b), the proposed scheme maintains the average travel time on both the main road and ramp road almost the same for every value of w_1. When the values of w_1 are 0.0 and 0.5, the proposed scheme considers the fairness of the assigned vehicle merging times on both the main and ramp roads. When the value of w_1 is 1.0, the proposed scheme preferentially assigns merging times to vehicles on a congested road to achieve maximization of outflow traffic. By continuously assigning merging times to vehicles on a congested road, the proposed scheme alternately assigns merging times to vehicles on both the main and ramp roads. As a result, the proposed scheme can maintain the average travel time on both the main and ramp roads almost the same for every value of w_1. Furthermore, since the proposed scheme improves outflow traffic from a highway on-ramp as the value of w_1 increases, the proposed scheme can also decrease the average travel time of vehicles on both the main and ramp roads as the value of w_1 increases.



(a) Comparison between FIFO, previous, and proposed with $w_1 = 0.5$



(b) Comparison among proposed schemes with different values of w_1

FIGURE 7. Vehicle density on both the main and ramp road vs time in a simulation.

3) VEHICLE DENSITY VS TIME IN A SIMULATION

To show the influence on the vehicle density when the inflow traffic of a ramp road is high, we fix the value of r_{main} to 0.7. In Fig. 7, we show a comparison between the FIFO, previous, and proposed scheme in terms of the vehicle density at a time in a simulation. The proposed scheme and FIFO scheme can maintain the vehicle density on both the main and ramp roads almost the same. This is because these schemes can fairly assign merging times to vehicles on both the main and ramp roads. Furthermore, the proposed scheme can keep the vehicle density on both the main and ramp roads lower than other schemes. This is because the proposed scheme considers both the optimality of outflow traffic and the fairness in assigned merging times. Since the proposed scheme improves outflow traffic from a highway on-ramp, the scheme can decrease the vehicle density on both the main and ramp roads.

As shown in Fig. 7(b), the proposed scheme with every value of w_1 keeps the vehicle density on both the main and ramp roads almost the same at every time in a simulation. When the values of w_1 are 0.0 and 0.5, the proposed scheme considers the fairness of the assigned vehicle merging times on both the main and ramp roads. As a result, the proposed scheme distributes the vehicle density on both the main and ramp roads. In addition, when the value of w_1 is 1.0, the proposed scheme maintains a low vehicle density on both the main and ramp roads. This is because the proposed scheme assigns merging times to vehicles such that their average speed is maximized. Since there is a negative correlation between the vehicle density and vehicle speed, the proposed scheme decreases the vehicle density on both the main and ramp roads. From the result, when the value of w_1 is 1.0, the proposed scheme distributes the vehicle density on both the main and ramp roads by alternately assigning merging times to vehicles on congested roads.

B. SCENARIO 2

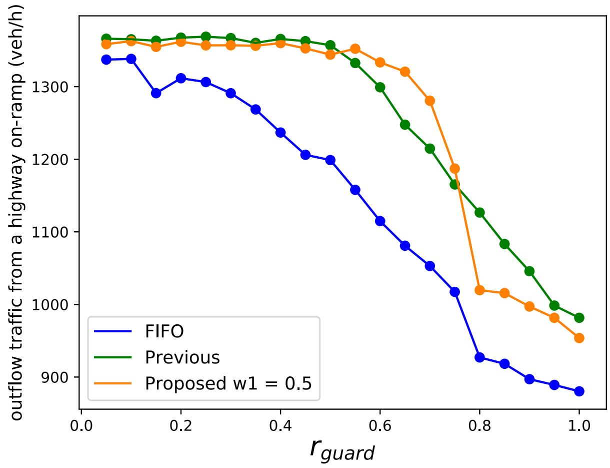
In this scenario, we changed r_{guard} from 0.0 to 1.0. The value of r_{main} was fixed to 0.4. This is because the simulation results of the FIFO, previous, and proposed scheme are almost the same in scenario 1 when the value of r_{main} is 0.4.

1) OUTFLOW TRAFFIC FROM A HIGHWAY ON-RAMP VS r_{guard}

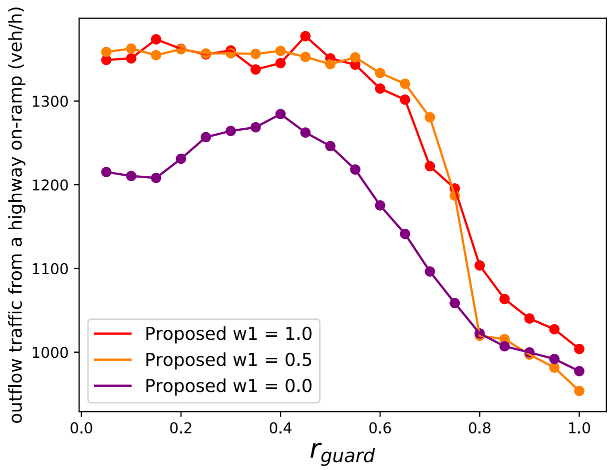
In Fig. 8, we show a comparison between the FIFO, previous scheme, and proposed scheme in terms of outflow traffic. The outflow traffic from a highway on-ramp of the proposed scheme and previous scheme decreases from $r_{guard} = 0.65$. This is because the total inflow traffic exceeds the maximum outflow traffic of a highway on-ramp. Since a vehicle passes a highway on-ramp per t_{head} or t_{guard} seconds, the maximum outflow traffic is estimated by the following calculation:

$$\text{maximum outflow traffic} \fallingdotseq \frac{3600.0}{min(t_{head}, t_{guard})}. \tag{25}$$

Specifically, when r_{guard} is 0.65, the maximum outflow traffic of a highway on-ramp is estimated as $3,600.0/(4.0 \cdot 0.65) \fallingdotseq 1,384$ veh/h. Since the total inflow traffic of both the main and ramp roads is 1,400 veh/h and it exceeds the maximum outflow traffic, the outflow traffic of the proposed scheme and the previous scheme start to decrease from $r_{guard} = 0.65$. 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 t_{guard} is higher than that of the other schemes. Since the opportunity for vehicles on both the main and ramp roads to alternatively merge onto a highway on-ramp is higher than that of other schemes, the outflow traffic of the FIFO scheme becomes low at every value of r_{guard}.



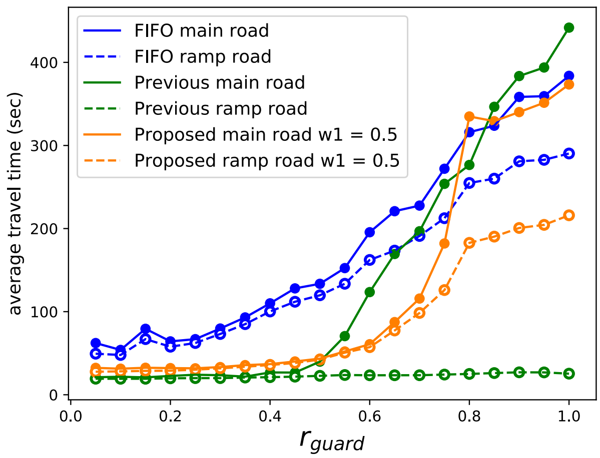
(a) Comparison between FIFO, previous, and proposed with $w_1 = 0.5$



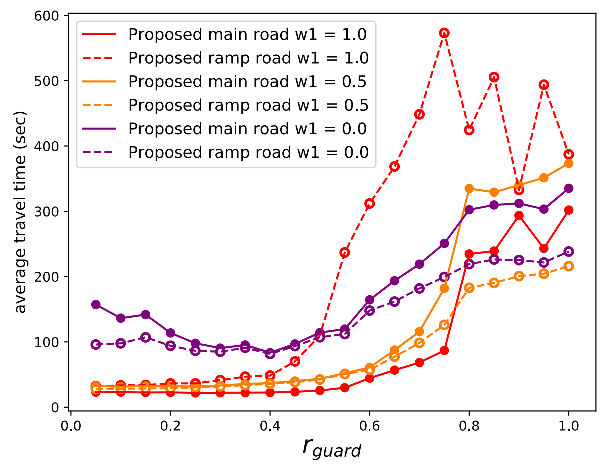
(b) Comparison among proposed schemes with different values of w_1

FIGURE 8. Outflow traffic from a highway on-ramp vs the ratio of minimum headway time on the same road to minimum headway time on different roads, r_{guard}.

As shown in Fig. 8(b), the outflow traffic of the proposed scheme does not change even if the value of w_1 changes from 0.5 to 1.0. This is because the safe headway time on different roads t_{guard} is low. In general, the main reason for decreasing outflow traffic from a highway on-ramp is that the frequency of t_{guard} becomes high. Since the frequency of t_{guard} increases as inflow traffic from a ramp road becomes high, the outflow traffic of the proposed scheme does not change when the value of r_{main} is 0.4. However, when the value of w_1 is 0.0, the outflow traffic is lower than that of the proposed scheme with other values of w_1. When the value of w_1 is 0.0, the proposed scheme considers only the fairness in vehicle merging times. As a result, the proposed scheme produces a high frequency of t_{guard} as well as the FIFO scheme. Hence, the outflow traffic of the proposed scheme becomes low when the value of w_1 is 0.0.



(a) comparison between FIFO, previous, and proposed with $w_1 = 0.5$



(b) Comparison among proposed schemes with different values of w_1

FIGURE 9. Average travel time of vehicles vs the ratio of minimum headway time on the same road to minimum headway time on different roads, r_{guard}.

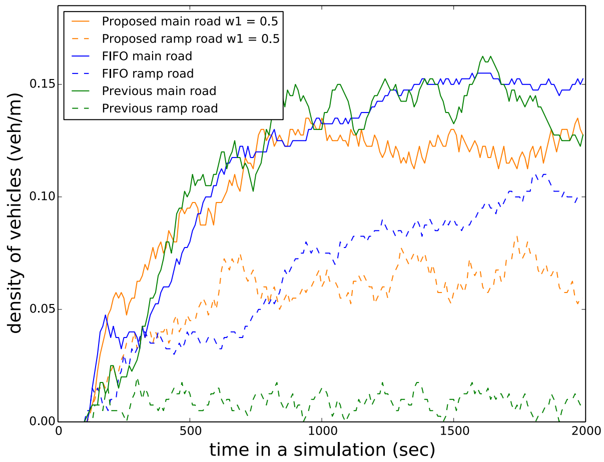
2) AVERAGE TRAVEL TIME OF VEHICLES VS r_{guard}

To show the fairness of the assigned merging times, we evaluate the average travel time of vehicles on both the main and ramp roads in Fig. 9. The proposed scheme can maintain the average travel time of both the main and ramp roads almost the same as the FIFO scheme when the value of r_{guard} is less than 0.8. In contrast, the difference between the average travel time of the proposed scheme on the main road and that on a ramp road increases as the value of r_{guard} is not less than 0.8. This is because the proposed scheme cannot allocate enough outflow traffic for the inflow traffic of the main road. Since the proposed scheme fairly assigns merging times to vehicles on both the main and ramp roads, the scheme also fairly allocates outflow traffic for both the inflow traffic of the main road and that of a ramp road. In contrast, the maximum outflow traffic decreases as r_{guard} increases along with (25). Therefore, since the inflow traffic of the main road is higher than that of a ramp road, the proposed scheme cannot allocate enough outflow traffic for the inflow traffic of the main road. Hence, traffic congestion occurs on the main road, and the average travel time of vehicles on the main road is delayed. The proposed scheme decreases the average vehicle travel time compared with the FIFO scheme. This is because the proposed scheme improves outflow traffic from a highway on-ramp compared with the FIFO scheme. In contrast, with these schemes, the previous scheme cannot maintain the average travel times of both the main and ramp roads almost the same. This is because the previous scheme preferentially assigns merging times to vehicles on a ramp road to group them. Since maximum outflow traffic from a highway on-ramp decreases as r_{guard} increases along with (25), the previous scheme allocates considerable outflow traffic for inflow traffic of a ramp road as r_{guard} increases. As a result, the previous scheme cannot allocate enough outflow traffic for the inflow traffic of the main road, and the assigned vehicle merging times on the main road is delayed.

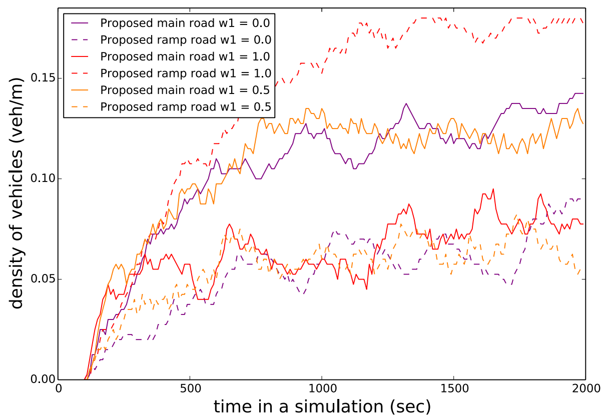
As shown in Fig. 9(b), when the values of w_1 are 0.0 and 0.5, the proposed scheme can keep the average travel time of vehicles on both the main and ramp roads almost the same. This result indicates that the proposed scheme fairly assigns merging times to vehicles on both the main and ramp roads when the values of w_1 are 0.0 and 0.5. In contrast, when the value of w_1 is 1.0, the proposed scheme cannot keep the average travel time of vehicles on both the main and ramp roads almost the same. This is because the proposed scheme preferentially assigns merging times to vehicles on the main road to maximize outflow traffic from a highway on-ramp. Since maximum outflow traffic from a highway on-ramp decreases as r_{guard} increases along with (25), the proposed scheme allocates much outflow traffic for inflow traffic of the main road as r_{guard} increases. As a result, the proposed scheme cannot allocate enough outflow traffic for inflow traffic of a ramp road, and the assigned vehicle merging times on a ramp road is delayed. Therefore, when the value of w_1 is 1.0, the proposed scheme cannot fairly assign the vehicle merging times on both the main and ramp roads.

3) VEHICLE DENSITY VS TIME IN A SIMULATION

To show the influence on the vehicle density when the value of r_{guard} is high, we fix the value of r_{guard} to 0.8. In Fig. 10, we show a comparison between the FIFO, previous, and proposed scheme in terms of the vehicle density at time in a simulation. The difference between the vehicle density on both the main and ramp roads of the proposed scheme is smaller than that of the previous scheme at every time in a simulation. This result indicates that the proposed scheme can distribute the vehicle density on both the main and ramp roads compared with the previous scheme. Furthermore, the vehicle density on both the main and ramp roads is lower than that



(a) Comparison between FIFO, previous, and proposed with $w_1 = 0.5$



(b) Comparison among proposed schemes with different values of w_1

FIGURE 10. Vehicle density on both the main and ramp road vs time in a simulation.

of the FIFO scheme at every time in a simulation. Since the proposed scheme improves outflow traffic compared with the FIFO scheme, the proposed scheme can decrease the vehicle density on both the main and ramp roads compared with the FIFO scheme.

As shown in Fig. 10(b), when the value of w_1 is 1.0, the difference between both the vehicle density on the main road and that on a ramp road of the proposed scheme is larger than that of the proposed scheme with the other values of w_1. This is because the proposed scheme assigns merging times only to vehicles on the main road. When the value of r_{guard} is 0.8, the maximum outflow traffic of a highway on-ramp is estimated as $3,600.0/(4.0 \cdot 0.8) \fallingdotseq 1125$ veh/h along with (25). The value of inflow traffic of the main road is 1,000 veh/h and is close to the value of maximum outflow traffic of a highway on-ramp. Since the proposed scheme only ensures optimality of outflow traffic when the value of w_1 is 1.0, it tends to assign merging times only to vehicles on the main road. In particular, the tendency becomes strong as the total inflow traffic becomes close to the maximum outflow traffic of a highway on-ramp because the proposed scheme cannot allocate enough outflow traffic for the inflow traffic of a ramp road. Furthermore, as the value of w_1 changes from 0.5 to 1.0, a congested road changes from the main road to a ramp road. The proposed scheme preferentially assigns merging times to vehicles on a road where inflow traffic is higher than on another road as the value of w_1 becomes close to 1.0. Therefore, the proposed scheme can determine whether to preferentially assign merging times to vehicles on a road with high inflow traffic or those on a road with low inflow traffic by setting a value of w_1 between 0.5 and 1.0.

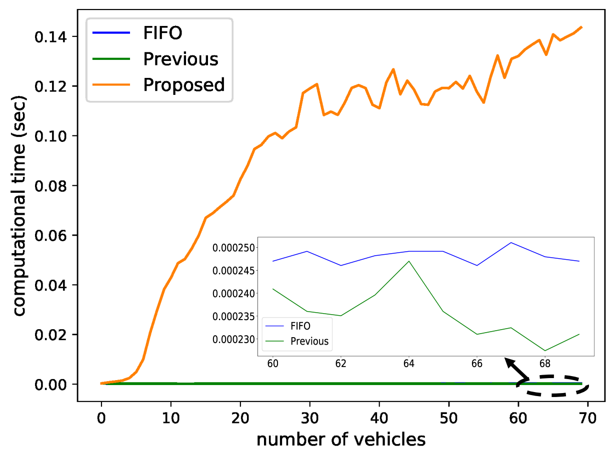


FIGURE 11. Computational time vs number of vehicles.

C. CALCULATION TIME VS NUMBER OF VEHICLES

In Fig. 11, we show a comparison between the FIFO, previous, and proposed scheme in terms of computational time. The computational time of both FIFO and the previous scheme is very short. This is because these schemes formulate their scheduling problems as linear formulations. In contrast, the computational time of the proposed scheme is longer than that of the other schemes. This is because the proposed scheme takes a heuristic approach to seek the optimal vehicle merging times. However, the computational time of the proposed scheme is on the order of a hundred milliseconds. This is because the proposed scheme takes an approach to group vehicles on a road by each segment of the road. By grouping vehicles on a road by each segment, the proposed scheme decreases the computational time to a few milliseconds. This computational time is equivalent to the computational time of the recent scheme, the purpose of which is to decrease computational time based on a heuristic approach for practical use [28]. Therefore, we argue that the computational time of the proposed scheme is short enough for practical use.

D. DISCUSSIONs

In practical use, the inflow traffic of both the main and ramp roads changes dynamically. Therefore, we have to determine the weight of the outflow traffic maximization

w_1 according to the inflow traffic dynamically. Let $f_{in}^{main}(t)$, $f_{in}^{ramp}(t)$, $k^{main}(t)$, and $k^{ramp}(t)$ denote inflow traffic of a main road, that of a ramp road, vehicle density on a main road, and that on a ramp road at time t, respectively. These values can be measured by counting the number of vehicles entering both the main and ramp roads. Without loss of generality, we assume that $k^{main}(t)$ is higher than $k^{ramp}(t)$ and try to decrease $k^{main}(t)$ for controlling road vehicle density. According to the inflow traffic, the traffic conditions are classified into two types which are as follows: (1) the sum of $f_{in}^{main}(t)$ and $f_{in}^{ramp}(t)$ is less than the maximum outflow traffic and (2) the sum of $f_{in}^{main}(t)$ and $f_{in}^{ramp}(t)$ exceeds the maximum outflow traffic. Both the traffic conditions have been shown in scenarios 1 and 2, respectively.

In the traffic condition of type 1, as shown in Fig. 7, $k^{main}(t)$ and $k^{ramp}(t)$ become almost the same continuously for every value of w_1. Furthermore, as shown in Figs. 5 and 6, the proposed scheme with $w_1 = 1.0$ is the most effective in terms of the outflow traffic and average travel time compared with the proposed schemes with the other values of w_1. Therefore, the proposed scheme brings w_1 to 1.0.

In the traffic condition of type 2, the difference between $k^{main}(t)$ and $k^{ramp}(t)$ gradually increases. Therefore, the proposed scheme has to control $k^{main}(t)$ and $k^{ramp}(t)$ by setting w_1 to the adequate value dynamically. As shown in Fig. 10, we have confirmed that the proposed scheme can control $k^{main}(t)$ and $k^{ramp}(t)$ by setting w_1 between 0.5 and 1.0. Furthermore, we have also confirmed that the proposed scheme with $w_1 = 1.0$ preferentially assigns merging times to vehicles on the road where inflow traffic is high. Therefore, if $f_{in}^{main}(t)$ is higher than $f_{in}^{ramp}(t)$, the proposed scheme brings w_1 to 1.0 to decrease $k^{main}(t)$. Otherwise, the proposed scheme brings w_1 to 0.5 to decrease $k^{main}(t)$.

V. CONCLUSION

In this paper, we proposed a scheduling scheme for autonomous vehicle highway merging with an outflow traffic and fairness analysis. To achieve outflow traffic maximization from a highway on-ramp, the proposed scheme assigns merging times to vehicles such that their average speed is maximized. To achieve the fairness in assigned merging times, the proposed scheme assigns merging times to vehicles such that the difference between their average speed on the main road and that on a ramp road is minimized. Simulation results show that the proposed scheme outperforms the FIFO-based scheme and previous optimization-based scheme in terms of outflow traffic from a highway on-ramp and fairness in assigned merging times. As a result, the proposed scheme mitigates the potential traffic congestion of the schemes. Specifically, we confirmed that the proposed scheme mitigated the potential traffic congestion by attaching importance to outflow traffic maximization when inflow traffic becomes high. Furthermore, we also confirmed that the proposed scheme mitigated the potential traffic congestion by attaching importance to both outflow traffic maximization and the fairness of the assigned merging times when the total inflow traffic becomes close to the maximum outflow traffic of a highway on-ramp.

REFERENCES

[1] J. Rios-Torres and A. A. Malikopoulos, "A survey on the coordination of connected and automated vehicles at intersections and merging at highway on-ramps," *IEEE Trans. Intell. Transp. Syst.*, vol. 18, no. 5, pp. 1066–1077, May 2017.

[2] A. A. Malikopoulos and J. P. Aguilar, "Optimization of driving styles for fuel economy improvement," in *Proc. 15th Int. IEEE Conf. Intell. Transp. Syst.*, Sep. 2012, pp. 194–199.

[3] V. L. Knoop, H. J. Van Zuylen, and S. P. Hoogendoorn, "Microscopic traffic behaviour near incidents," in *Transportation and Traffic Theory 2009: Golden Jubilee*, W. Lam, S. Wong, and H. Lo, Eds. Boston, MA, USA: Springer, 2009, doi: 10.1007/978-1-4419-0820-9_5.

[4] A. A. Malikopoulos and J. P. Aguilar, "An optimization framework for driver feedback systems," *IEEE Trans. Intell. Transp. Syst.*, vol. 14, no. 2, pp. 955–964, Jun. 2013.

[5] *An Agency Guide on How to Establish Localized Congestion Mitigation Programs, United States*. Federal Highway Administration. Office of Operations, Accessed: Aug. 17, 2020. [Online]. Available: https://ops.fhwa.dot.gov/publications/fhwahop11009/fhwahop11009.pdf

[6] M. Won, T. Park, and S. H. Son, "Toward mitigating phantom jam using vehicle-to-vehicle communication," *IEEE Trans. Intell. Transp. Syst.*, vol. 18, no. 5, pp. 1313–1324, May 2017.

[7] L. Li, D. Wen, and D. Yao, "A survey of traffic control with vehicular communications," *IEEE Trans. Intell. Transp. Syst.*, vol. 15, no. 1, pp. 425–432, Feb. 2014.

[8] R. Metering, "A proven, cost-effective operational strategy a primer," U.S. Dept. Transp. Federal Highway Admin., Washington, DC, USA, Tech. Rep. FHWA-HOP-14-020, 2019. Accessed: Nov. 26, 2019. [Online]. Available: https://ops.fhwa.dot.gov/publications/publications.htm

[9] H. Hadj-Salem, J. M. Blosseville, and M. Papageorgiou, "ALINEA: A local feedback control law for on-ramp metering; a real-life study," in *Proc. 3rd Int. Conf. Road Traffic Control*, London, U.K., 1990, pp. 194–198.

[10] T. Bellemans, B. De Schutter, G. Wets, and B. De Moor, "Model predictive control for ramp metering combined with extended Kalman filter-based traffic state estimation," in *Proc. IEEE Intell. Transp. Syst. Conf.*, Toronto, ON, Canada, Sep. 2006, pp. 406–411.

[11] A. H. Ghods, L. Fu, and A. Rahimi-Kian, "An efficient optimization approach to real-time coordinated and integrated freeway traffic control," *IEEE Trans. Intell. Transp. Syst.*, vol. 11, no. 4, pp. 873–884, Dec. 2010.

[12] A. Fares and W. Gomaa, "Freeway ramp-metering control based on reinforcement learning," in *Proc. 11th IEEE Int. Conf. Control Autom. (ICCA)*, Taichung, Taiwan, Jun. 2014, pp. 1226–1231.

[13] C. J. C. H. Watkins and P. Dayan, "Q-learning," *Mach. Learn.*, vol. 8, nos. 3–4, pp. 279–292, 1992.

[14] V. Milanes, J. Godoy, J. Villagra, and J. Perez, "Automated on-ramp merging system for congested traffic situations," *IEEE Trans. Intell. Transp. Syst.*, vol. 12, no. 2, pp. 500–508, Jun. 2011.

[15] Y. Hou, P. Edara, and C. Sun, "Modeling mandatory lane changing using Bayes classifier and decision trees," *IEEE Trans. Intell. Transp. Syst.*, vol. 15, no. 2, pp. 647–655, Apr. 2014.

[16] J. Rios-Torres and A. A. Malikopoulos, "Automated and cooperative vehicle merging at highway on-ramps," *IEEE Trans. Intell. Transp. Syst.*, vol. 18, no. 4, pp. 780–789, Apr. 2017.

[17] T. Awal, L. Kulik, and K. Ramamohanrao, "Optimal traffic merging strategy for communication- and sensor-enabled vehicles," in *Proc. 16th Int. IEEE Conf. Intell. Transp. Syst. (ITSC)*, Oct. 2013, pp. 1468–1474.

[18] J. Ding, L. Li, H. Peng, and Y. Zhang, "A rule-based cooperative merging strategy for connected and automated vehicles," *IEEE Trans. Intell. Transp. Syst.*, vol. 21, no. 8, pp. 3436–3446, Aug. 2020.

[19] B. van Arem, C. J. G. van Driel, and R. Visser, "The impact of cooperative adaptive cruise control on traffic-flow characteristics," *IEEE Trans. Intell. Transp. Syst.*, vol. 7, no. 4, pp. 429–436, Dec. 2006.

[20] M. Yoshida, H. Asahina, H. Shigeno, and I. Sasase, "A scheduling scheme for cooperative merging at a highway on-ramp with maximizing average speed of automated vehicles," in *Proc. IEEE 92nd Veh. Technol. Conf. (VTC-Fall)*, Victoria, BC, Canada, Nov. 2020, pp. 1–5.

[21] H. Rakha and B. Crowther, "Comparison of Greenshields, Pipes, and Van Aerde car-following and traffic stream models," *Transp. Res. Rec., J. Transp. Res. Board*, vol. 1802, no. 1, pp. 248–262, Jan. 2002.

[22] B. D. Greenshields, "A study of traffic capacity," in *Proc. Highway Res. Board*, 1935, pp. 448–477.
[23] M. Behrisch, L. Bieker, J. Erdmann, and D. Krajzewicz, "SUMO–simulation of urban mobility: An overview," in *Proc. 3rd Int. Conf. Adv. Syst. Simulation*, 2011, pp. 63–68.
[24] S. Krauss, P. Wagner, and C. Gawron, "Metastable states in a microscopic model of traffic flow," *Phys. Rev. E, Stat. Phys. Plasmas Fluids Relat. Interdiscip. Top.*, vol. 55, no. 5, pp. 5597–5602, May 1997.
[25] J. Forrest, T. Ralphs, S. Vigerske, L. Hafer, J. B. Kristjansson, E. Straver, M. Lubin, R. H. G. Santos, and M. Saltzman. *Coin-Or/CBC: Version 2.9.9*. Accessed: Jul. 2018. [Online]. Available: https://zenodo.org/record/1317566#.YFrex0gzZb8
[26] R. Tachet, P. Santi, S. Sobolevsky, L. I. Reyes-Castro, E. Frazzoli, D. Helbing, and C. Ratti, "Revisiting street intersections using slot-based systems," *PLoS ONE*, vol. 11, no. 3, pp. 1–9, Mar. 2016.
[27] S. A. Fayazi and A. Vahidi, "Mixed-integer linear programming for optimal scheduling of autonomous vehicle intersection crossing," *IEEE Trans. Intell. Vehicles*, vol. 3, no. 3, pp. 287–299, Sep. 2018.
[28] H. Xu, S. Feng, Y. Zhang, and L. Li, "A grouping-based cooperative driving strategy for CAVs merging problems," *IEEE Trans. Veh. Technol.*, vol. 68, no. 6, pp. 6125–6136, Jun. 2019.

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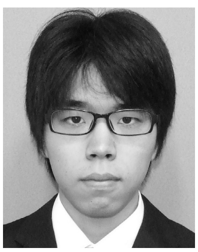

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