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Optimization of Traffic Efficiency at On-ramps with Connected Automated Vehicles

Na Chen, Bart van Arem, and Meng Wang

Abstract— **This paper aims to optimize on-ramp merging processes for connected automated vehicles by utilizing an existing hierarchical control architecture including a decision-maker and an operational controller. The decision-maker employs surrogate linear models to predict future vehicular acceleration analytically and computes a merging sequence to minimize merging times of on-ramp vehicles. The operational controller is formulated as a model predictive control problem, which utilizes a second-order vehicle dynamics model, and regulates vehicles' accelerations and time instants to execute lateral movements of on-ramp vehicles for the merging processes respectively. Constraints on vehicular acceleration, speed, and inter-vehicle distance are considered by the decision-maker and the operational controller for practical usage. The proposed method to minimize the merging times of on-ramp vehicles and a *first-in-first-out* method are tested under different initial settings, including initial vehicular speeds, distributions of vehicular positions, and desired time gaps. The simulation results show that the proposed method is superior to the first-in-first-out method widely used in literature in improving merging traffic efficiency. We find that cooperation among vehicles makes the on-ramp vehicles join mainline traffic faster, and the acceptable time gap for merging affect choices of optimal merging sequences.**

I. Introduction

Traffic congestion near on-ramps brings economical loss to society and affects traffic efficiency. Researchers focus on finding or improving feasible measures such as ramp metering, in-vehicle advice, variable speed limits, or concentrate on trajectory planning for automated vehicles to alleviate traffic congestion. Connected Automated Vehicles (CAVs) are equipped with Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communications to share vehicular information or send instructions. CAVs' trajectories can be regulated together to achieve a common goal related to traffic operations.

With CAVs, traffic operations near bottlenecks on highways can be improved [1, 2]. [3] finds that with shared vehicular information, CAVs have the potential to increase highway capacity and to reduce traffic instability when the market penetration of the CAVs is higher than 40% near a lane-drop bottleneck. Merging process near on-ramps can be achieved by finding a suitable gap to cut in for an on-ramp CAV while the CAV is on the acceleration lane or by regulating CAVs' trajectories cooperatively to create a large enough gap for the CAV to accomplish mandatory lane changing. Merging sequences or selected or created gaps for on-ramp vehicles affect traffic efficiency during the merging process[2, 4, 5].

Merging sequences are established resting on different methods. The virtual mapping method works by mapping on-ramp vehicles' positions to the object lane of mainline traffic and establishes merging sequences by sorting distances of vehicles to a merging point [5-7]. The *first-in-first-out* method makes a vehicle entering a control zone first leave the control zone first [8]. The *first-come-first-serve* chooses a vehicle closer to an intersection to enter into the intersection earlier [9]. The merging sequences can also be decided according to whether a large enough gap is available or can be created. [10] makes CAVs act as leaders and collect inter-vehicle spaces into gaps by using a fundamental diagram of traffic flow. When a large gap is generated, an on-ramp vehicle is allowed to merge into mainline traffic. If future vehicles' states, such as fixed merging speed or inter-vehicle distance near a merging point, are prescribed, merging sequences are established to meet the requirements for all vehicles [11]. [12] employs virtual slots as possible locations of CAVs. Inter-vehicle distances are non-negative because they are restricted by the distance between consecutive virtual slots.

Given different merging sequences, an operational controller, based on optimal control, fuzzy control, or cooperative adaptive control, regulates vehicles' trajectories to have large enough inter-vehicle distance to create suitable merging conditions [5-8, 13]. Different merging sequences can trigger different performances of traffic operations. Different performance indicators are selected to show traffic operations near on-ramps or lane-drop bottlenecks where mandatory lane-change demand exists, such as average travel time, traffic capacity, merging times of on-ramp vehicles, average speed, a value of an elaborated cost or objective function, traffic stability or emission [14, 15].

One way to optimize traffic operation is by evaluating all different or feasible merging sequences with some selected performance indicators [16, 17]. In our previous study, we proposed a hierarchical architecture of the merging control system and found that speed-adaptation time instant when an on-ramp vehicle starting to adapt its speed and position to merge into the target gap should be considered to improve traffic operations [18]. The merging time for an on-ramp vehicle is the time duration for it to pass through the on-ramp and accomplish merging into mainline traffic. Average

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merging time of on-ramp vehicles is selected as a performance indicator for evaluating traffic operation in literature [15]. However, how to achieve a minimal merging time of an on-ramp CAV is not known especially considering its speed-adaptation time instant.

This paper aims to minimize the merging time of on-ramp vehicles by utilizing an existing hierarchical architecture of the merging control system proposed in our previous research [18]. The hierarchical control architecture includes a decision-maker and an operational layer controller. The decision-maker establishes merging sequences and speed-adaptation time instants for the involved merging vehicles; the operational controller regulates vehicles' trajectories to accomplish merging maneuvers.

The paper is organized as follows. Firstly, the hierarchical control architecture is briefly introduced and assumptions are given. After that, formulations for the decision-maker and operational layer controller are presented, followed by simulations setup. The experimental results are then analyzed and discussed. Finally, a conclusion is given.

II. Hierarchical Control Architecture

This section briefly introduces the hierarchical control architecture and assumptions in the control design.

In this paper, a bottleneck with a main lane (numbered lane 2) and a single on-ramp lane (numbered lane 1) leading to an acceleration lane (numbered lane 1) are considered as shown in Fig. 1. All vehicles are CAVs and they are controlled automatically by a decision-maker, located in a road-based traffic management center, and an operational controller, located in each CAV. When CAVs travels as a platoon, the leader acts as the operational controller to give control commands to CAVs in the platoon.

The hierarchical control architecture is as shown in Fig. 2. Mainline and on-ramp CAVs send their vehicular information, such as vehicle number, including lane number as shown in Fig. 1, position and speed, to the decision-maker or operational controller through V2I communication and V2V communication respectively.

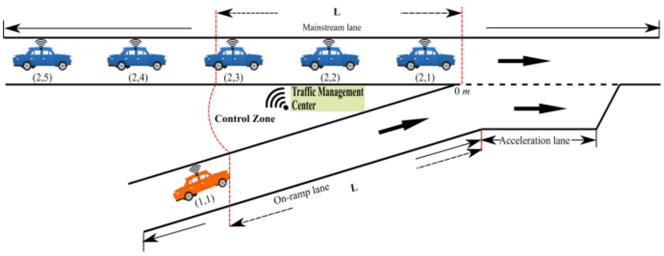

Figure 1. The topology of the on-ramp where cooperative merging takes place.

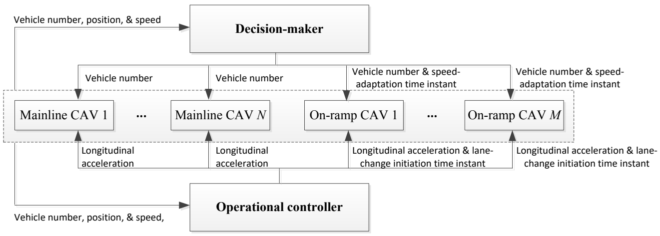

Figure 2. Hierarchical control architecture.

The decision-maker cyclically determines the merging sequence and speed-adaptation time instants for the on-ramp CAVs. The merging sequence can be connected to vehicle numbers which include vehicles' lane numbers. Before a given speed-adaptation time instant, an on-ramp CAV travels to reach or keep its desired speed, or follows its direct preceding vehicle in lane 1; after that time instant, the CAV starts to adjust its speed and position to reach between its new direct preceding and following vehicle. When a new on-ramp CAV shows up, the established vehicle numbers for the other on-ramp CAVs are not affected. The operational controller cyclically regulates CAVs' longitudinal accelerations and on-ramp CAVs' lane change initiation time instants when they start to steer towards the mainline traffic.

III. Formulations For Controllers

This section elaborates on the design for the decision-maker and operation controller in the hierarchical control architecture in this paper. Only one on-ramp vehicle shown in Fig.1 is considered each time to show how the decision-maker and operation controller work for clarity. However, our design is applicable to multiple on-ramp vehicles.

A. Decision-maker establishing future vehicle numbers

The decision-maker establishes future vehicle numbers for all CAVs and the speed-adaptation time instants for the on-ramp CAVs. Because every time, only one new on-ramp CAV is tackled to update decisions, only one CAV is considered as shown in Fig. 1. The initial vehicle numbers are shown in Fig. 1, including lane number and vehicle order in the lane.

The state variable is defined as $\mathbf{Z^D}$=($x_{\mathbf{U^D}(1)}$, $v_{\mathbf{U^D}(1)}$,…, $x_{\mathbf{U^D}(N+1)}$, $v_{\mathbf{U^D}(N+1)}$)^T, and the decision variable is defined as $\mathbf{U^D}$=($v^n{}_1$,…, $v^n{}_{N+1}$, t^{sa})^T, where $x_{\mathbf{U^D}(i)}$, $v_{\mathbf{U^D}(i)}$, $v^n{}_i$, and t^{sa} stand for location and speed of vehicle $\mathbf{U^D}(i)$, vehicle number of the ith vehicle, and the speed-adaptation time instant of the on-ramp vehicle, i=1,.., N+1. The initial value of $v^n{}_i(0)$ is (2,i), i=1,.., N, and of $v^n{}_{N+1}(0)$ is (1,1). For simplicity, the time argument or subscript is dropped where no misunderstanding exists and the final value of $v^n{}_{N+1}$ is given (2,k).

A second-order vehicle dynamics model, Eq. (1), is employed, where a is acceleration. The acceleration for CAVs is generated through two modes: car-following and cruising mode. The car-following mode, shown in Eq. (2) [3], works when a vehicle has a vehicle number with a lane number equaling to 2. It also applies to an on-ramp vehicle when an on-ramp vehicle is close to its direct preceding vehicle in lane 1 by changing the lane number in Eq. (2) to 1. Cruising mode, shown in Eq. (3) [3], works for an on-ramp vehicle before its speed-adaptation time instant if it does not has a direct preceding vehicle in lane 1. Both car-following and cruising modes work together with the boundary on the maximum acceleration $a_{\max}$ and the minimum deceleration $a_{\min}$ to make the design practical.

$$\dot{x} = v\,,\ \dot{v} = a \tag{1}$$

$$\begin{aligned} a_{(2,i)} &= D_1\cdot\left(x_{(2,i-1)} - x_{(2,i)} - l_{veh} - s^d_{(2,i)}\right) \\ &\quad + D_2\cdot\left(v_{(2,i-1)} - v_{(2,i)}\right) + D_3\cdot a_{(2,i-1)} \end{aligned} \tag{2}$$

$$a_{(1,1)} = D_4\cdot\left(v^{\text{limits}} - v_{(1,1)}\right) \tag{3}$$

where, $s^d_{(2,i)}=v_{(2,i)} \cdot t^d+s_0$ is the desired inter-vehicle gap of vehicle (2,i); D_1, D_2, D_3, and D_4, are parameters; l_{veh}, v^{limits}, t^d, and s_0 are the length of a vehicle, speed limits, desired time gap, and the inter-vehicle distance at standstill.

The acceptable time gap t^{atg} for the on-ramp vehicle to change lane decreases when it is approaching the end of the acceleration lane as shown in Eq. (4).

$$t^{atg} = \left(x_{(2,k)} - p_s\right)\cdot\left(t^d_{\min} - t^d\right)/\left(p_e - p_s\right) + t^d \tag{4}$$

where, p_s, p_e, and $t^d_{\min}$ stand for the start and end of the acceleration lane, and the minimum time gap to change lane respectively.

The decision-maker establishes decisions for a time horizon T, using time step $\Delta\tilde{t}$, to minimize the predicted merging time t^{mt} of the on-ramp vehicle based on Eq. (1), Eq. (2), Eq. (3), and Eq. (4). Its optimization problem is formulated as shown in Eq. (5).

$$\min_{\mathbf{U^D}[0,T]} t^{mt} \tag{5}$$

subject to:

- the vehicle dynamics model in Eq. (1).
- the car-following mode or the cruising mode in Eq. (2) and Eq. (3).
- the initial condition: $\mathbf{Z^D}(0)= \tilde{\mathbf{Z}}^{\mathbf{D}}(0)$, where $\tilde{\mathbf{Z}}^{\mathbf{D}}(0)$ represents the initial state for the controller at 0 s.
- the speed constraint: $0\le v\le v^{\text{limits}}$.
- the lane change condition: the time gaps between the on-ramp vehicle and its future preceding vehicle and following vehicle respectively are larger than t^{atg} when the on-ramp vehicle steers towards the mainline traffic on the acceleration lane.
- the acceleration constraint: $a_{\min} \le a\le a_{\max}$.

B. Operational controller regulating vehicular trajectories

The operation controller is designed based on Model Predictive Control (MPC) to regulate longitudinal accelerations for the CAVs and lane change initiation time instant t^{lc} for the on-ramp CAV. It utilizes the same second-order vehicle dynamics model as shown in Eq. (1).

For vehicles with lane number 2, they are controlled centrally, with the first vehicle acting as a leader, collecting vehicular information and distributing control decisions. Before t^{sa}, the on-ramp vehicle is self-controlled to reach or keep its desired speed if it is far away from its direct preceding vehicle or does not have a direct preceding vehicle; otherwise, it uses its direct preceding vehicles' information to calculate its acceleration. Here, we only give a general definition of state variable after t^{sa}. Before t^{sa}, mainline CAVs and the on-ramp CAV are not controlled together and the on-ramp CAV does not change lane; different state and control variables and different formulations are used to generate longitudinal accelerations.

$\mathbf{Z^O}=(x_{(2,1)},v_{(2,1)}, a_{(2,1)},\ldots, x_{(2,N+1)}, v_{(2,N+1)},a_{(2,N+1)},y_{(2,k)})^T$ is defined as the state variable and $\mathbf{U^O}=(u_{(2,1)},\ldots, u_{(2,N+1)},t^{lc})^T$ is defined as the control variable, where $y_{(2,k)}$is the lateral location of the on-ramp vehicle. After t^{lc}, the $y_{(2,k)}$changes according to a trajectory equation given a lane change execution time t^m [19, 20].

The operational layer controller regulates longitudinal accelerations for CAVs and t^{lc} for the on-ramp CAV by MPC for a time horizon T_p, shorter than T. After a time step Δt, shorter than $\Delta\tilde{t}$, new control commands are generated with a starting current time instant t_0. The formulation of the MPC process is as shown in Eq. (6).

$$\begin{aligned} \min_{\mathbf{U}^o[t_0,T_p]} &\int_{t_0}^{t_0+T_p} \left(c_1\cdot\sum_{i=2}^{N+1}\left(\Delta s^2_{(2,i)}\right) + c_2\cdot\sum_{i=2}^{N+1}\left(\Delta v^2_{(2,i)}\right) + c_3\cdot\sum_{i=2}^{N+1}\left(u^2_{(2,i)}\right)\right)dt \\ &+ c_4\cdot\sum_{i=2}^{N+1}\left(\Delta s^2_{(2,i)}\left(t_0+T_p\right)\right) + c_5\cdot\sum_{i=2}^{N+1}\left(\Delta v^2_{(2,i)}\left(t_0+T_p\right)\right) \end{aligned} \tag{6}$$

subject to:

- the vehicle dynamics model in Eq. (1).
- the speed constraint: $0\le v\le v^{\text{limits}}$.
- the initial condition: $\mathbf{Z^O}(t_0)= \tilde{\mathbf{Z}}^{\mathbf{O}}(t_0)$, where $\tilde{\mathbf{Z}}^{\mathbf{O}}(t_0)$ represents the initial state for the controller at t_0.
- the lane change condition: for future time t^m, the predicted time gaps between the on-ramp vehicle and its future preceding vehicle and following vehicle respectively are larger than t^{atg}, generated according to the on-ramp CAV's position at t_0.
- the acceleration constraint: $a_{\min} \le a\le a_{\max}$.
- the inter-vehicle gap constraint: $x_{vn(i)}- x_{vn(i+1)}- l_{veh} \ge s_0$, $i=1,2,\ldots,N-1$.

where, $\Delta s_{(2,i)}= x_{vn(i-1)}- x_{vn(i)}- l_{veh}- s^d_{(2,i)}$ and $\Delta v_{(2,i)}= v_{vn(i-1)}- v_{vn(i)}$.

Before t^{sa}, the formulation of the operational controller to generate mainline CAVs' longitudinal acceleration only utilizes or includes future vehicular information of N vehicles, excluding $vn(N+1)$, in Eq. (6) subject to constraints excluding the lane change condition constraint. When the on-ramp vehicle is close to its direct preceding vehicle in lane 1, Eq. (6) is used to generate the on-ramp vehicle's acceleration by changing lane number to 1 and using the preceding vehicle's information. When no preceding vehicle exists or the preceding vehicle is far away, the formulation of the operational controller to generate the on-ramp vehicle's longitudinal acceleration is as shown in Eq. (7) with $\mathbf{U^O}$ only having the on-ramp CAV's longitudinal acceleration subject to constraints listed above excluding lane change condition and inter-vehicle gap constraints.

$$\min_{\mathbf{U}^o[t_0,T_p]} \int_{t_0}^{t_0+T_p} \left(c_2 \cdot \left(v^{\text{limits}} - v_{(1,1)} \right)^2 + c_3 \cdot u_{(1,1)}^2 \right) dt \tag{7}$$

The solution method for Eq. (6) is the same as that used in [20], based on Pontryagin's Minimum Principle. Equation (7) is solved by using quadratic programming.

IV. Experimental Settings

In this section, the detailed design of different initial settings for simulations is described and the selected performance indicator to measure traffic operations is given.

A. Initial settings

To validate the hierarchical control approach, different scenarios are chosen by choosing different desired time gap and assigning different initial speeds and positions to the on-ramp vehicle. In total 5 mainline vehicles (N=5) and 1 on-ramp vehicle are used for the simulations, as shown in Fig. 1. The desired time gap is given 0.6 s, 0.8 s, 1 *s*, and 1.2 *s* respectively. The mainline vehicles are given initial speed 25 *m*/*s*. The initial speed for the on-ramp vehicle is given 15 *m*/*s*, 20 *m*/*s*, and 25 *m*/*s* respectively. For equilibrium scenarios, the inter-vehicle distances for mainline vehicles are initially desired inter-vehicle distance. The two initial relative positions for the on-ramp vehicle are chosen: 1) the on-ramp vehicle enters into the control zone together with a mainline vehicle, vehicle (2,3) being selected in this paper; 2) the on-ramp vehicle has the same longitudinal distance to vehicle (2,3) and vehicle (2,4) when it enters into the control zone [18]. The initial position for the on-ramp vehicle is a fixed value -62 *m*. The mainline vehicles' initial positions are calculated by using the on-ramp vehicle's position, the relative position type, and inter-vehicle distances between consecutive mainline vehicles. Besides, another experiment is set up with all mainline vehicles starting with large gaps (using time gap 1 *s*), with initial speed for the on-ramp vehicle being 15 *m*/*s*, initial position 2), and desired time gap 0.6 *s*. In total, 25 different initial settings.

B. Benchmark control method

The sections between two red dotted lines are within the control zone in Fig. 1, used by the *first-in-first-out* method to establish merging sequence, a vehicle entering into the control zone first leaving it first. If two vehicles enter into the control zone at the same time, the mainline vehicle leaves first. The benchmark control method uses the *first-in-first-out* method to establish merging sequences and utilizes the same operational controller to generate trajectories for vehicles. When no confusion exists, the *first-in-first-out* method is used as a replacement of the benchmark control method.

Because the on-ramp vehicle enters into the control zone at the same time with vehicle (2,3) or between the vehicle (2,3) and vehicle (2,4), the future vehicle order for the on-ramp vehicle is (2,4), with k=4 and t^{sa}=0 s, decided by the *first-in-first-out* method.

C. Parameters selection

The parameters are set as follows: D_1=0.2, D_2=0.7, D_3=0.8, D_4=1, c_1=0.1, c_2=0.5, c_3=0.5, c_4=0.1, c_5=0.1, T=120 *s*, T_p= 6 *s*, t_d= 1 *s*, v^{limit}=30 *m*/*s*, $a_{\max}$ = -4 *m*/*s*^{2}, $a_{\max}$= 2 *m*/*s*^{2}, t^m=5 *s*, s_0=2 *m*, p_s=0 *m*, p_e =300 *m*, and $t_{\min}{}^d$=0.25 *s*. The simulation time step is 0.1 *s*. The time steps used for the decision-maker and the operational controller are $\Delta \tilde{t}$ =0.5 *s* and Δt =0.1 *s* respectively. The initial value of t_0 is 0 *s*. The parameter used for the operational controller is the same as in [18]. The parameters D_1, D_2, D_3, and D_4 are manually tuned by making the decisions fit with real optimal decisions for different initial settings. The simulations are done with MATLAB R2018a. The total simulation time for using the operational controller to regulate vehicular trajectories is 50 *s*, enough for the on-ramp vehicle to merge into the mainline traffic.

D. Performance indicator

The objective of this paper is to minimize the merging time of the on-ramp vehicle. To this end, the selected performance indicator to show traffic operation is the merging time of the on-ramp vehicle. Besides, no collision is required.

V. Experimental Results And Discussion

In this section, the experimental results are given and analyzed, based on which a discussion is stated.

A. Starting from Equilibrium states

For the 24 scenarios where mainline vehicles start from the equilibrium state, only under 5 scenarios the hierarchical control approach gives different merging sequences and speed-adaptation time instants from the *first-in-first-out* method. 4 out of the 5 scenarios are with 25 *m*/*s* as the initial speed of on-ramp vehicle and with the on-ramp vehicle entering into the control zone together with the mainline vehicle (2,3). For these 4 scenarios, the *first-in-first-out* method gives k=4 and t^{sa}=0 *s*; the hierarchical control approach selects k=3 and t^{sa}=0 *s*. The merging time of the on-ramp vehicles under these 4 scenarios controlled by the two methods are as shown in Fig. 3. The difference is brought by the criterion defined to have the acceptable time gap for lane changing in Eq. (4).

Another scenario is that the desired time gap is 0.6 s, the initial speed of the on-ramp vehicle is 15 m/s, and the on-ramp vehicle has the same inter-vehicle distance to the mainline vehicle (2,3) and (2,4) when it enters into the control zone. For this scenario, using the *first-in-first-out* method leads to k=4 and t^{sa}=0 *s* and using the hierarchical control approach k=5 and t^{sa}=0 *s* or 0.5 *s*. The vehicle trajectories under the two different methods are as shown in Fig. 4 and Fig. 5. Fig. 5 shows the decision with t^{sa}=0.5 *s*.

In Fig. 4 and Fig. 5, the dotted lines stand for trajectories of the on-ramp vehicle before it changes lane and joins the mainline traffic. When the on-ramp vehicle changes lane, the inter-vehicle gaps are above 15 *m*. To this end, safety is ensured. At around 20 *s*, vehicles reach their equilibrium states with the *first-in-first-out* method. By comparison, the time used to reach their equilibrium states is shorter, around 15 *s*, when with the hierarchical control approach.

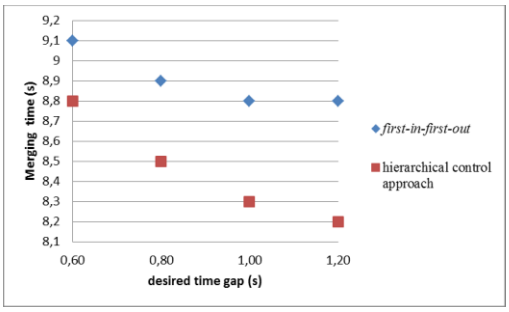

Figure 3. The performance comparison of two different control method under the 4/5 scenarios

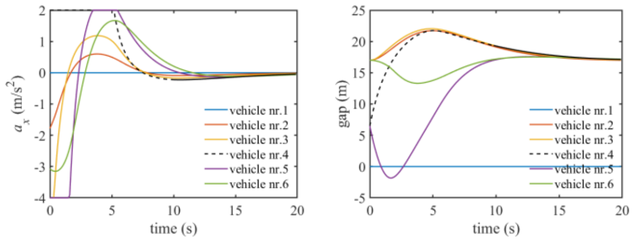

Figure 4. Vehicle trajectories when controlled by the *first-in-first-out* method.

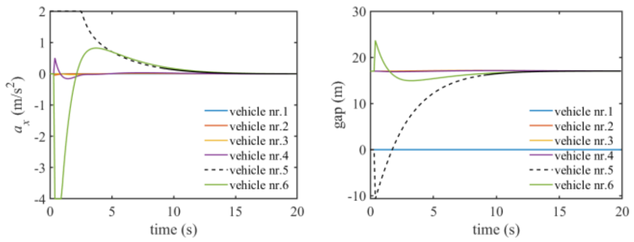

Figure 5. Vehicle trajectories when controlled by the hierarchical control approach.

The merging time of the on-ramp vehicle with the *first-in-first-out* method is 9.9 *s* but with the hierarchical control approach is 9.1 *s*, with t^{sa}=0 *s* or 0.5 *s*.

B. Starting from non-Equilibrium states

For the non-equilibrium states, all mainline vehicles have larger inter-vehicle distance than their desired values. The decision from the *first-in-first-out* method is k=4 and t^{sa}=0 *s* and from the hierarchical control approach k=5 and t^{sa}=0.5 or 1 *s*, leading to the merging time of the on-ramp vehicle being 9.6 *s* and 8.2 *s* or 8.3 *s* respectively. The deviation between 8.2 *s* and 8.3 *s* is acceptable because the time step used for the decision-maker is 0.5 *s*.

C. Discussion

When all vehicles are automated vehicles, some literature selects the merging times of on-ramp vehicles as a performance indicator to show traffic efficiency without a clear explanation. In this paper, we use the hierarchical control approach elaborated in [18] to explore the optimal merging sequences bringing the minimal merging times and explain the decreased merging times with connected automated vehicles.

Experimental results show that a speed-adaptation time instant is not necessarily to be considered to have the minimal merging time of an on-ramp vehicle. The on-ramp vehicle should be assigned a merging sequence immediately after it enters into the on-ramp lane and detected to have minimal merging times. Compared with human-driven vehicles, connected automated vehicles are given a merging sequence before reaching the start of the acceleration lane and prepare inter-vehicle gaps for merging earlier. To this end, the merging times are averagely reduced.

An optimal merging sequence has a relationship with the initial speed of the on-ramp vehicle, the desired time gap, the acceptable time gap for merging, and the on-ramp vehicle's relative position to mainline traffic when it enters into the control zone. When the initial speed of an on-ramp vehicle is low and it enters into the control zone together with a mainline vehicle, the optimal merging sequence is to take the mainline vehicle as its directly preceding vehicle. When the initial speed of an on-ramp vehicle is low and it enters into the control zone between two mainline vehicles, it may choose to merge between the two vehicles when the desired time gap is large or after them when the desired time gap is small. When the initial speed of an on-ramp vehicle is the same as the mainline traffic and it enters into the control zone together with a mainline vehicle, the optimal merging sequence is to take the mainline vehicle as its directly following vehicle; otherwise, the optimal merging sequence is to take the mainline vehicle as its directly preceding vehicle.

The hierarchical control approach works better than the *first-in-first-out* method in improving traffic operations and reducing merging times of on-ramp vehicles. The optimality of decisions from the hierarchical control approach is manually tested by changing the value of the speed-adaptation time instants and merging sequences. The feasibility of the hierarchical control approach is demonstrated with this paper and our previous research [18]. With different performance indicators, the optimal merging sequence can be different.

VI. CONCLUSION

This paper utilizes a hierarchical control approach to explore the optimal merging sequence to minimize merging times of on-ramp vehicles. The hierarchical control approach includes a decision-maker and an operational controller. The decision-maker establishes merging sequences and speed-adaptation time instants by minimizing the merging times of on-ramp vehicles for a long time horizon. It employs analytical linear equations with bounded acceleration to predict vehicular trajectories during the merging process. The operational controller optimizes vehicular trajectories and creates large enough target inter-vehicle gaps for on-ramp vehicles to accomplish the merging process.

The performance of the hierarchical control approach and a *first-in-first-out* method is tested with simulations under 25 scenarios. The experimental results show that for scenarios where an on-ramp vehicle has the same or similar speed as mainline traffic, the two control methods give the same control command when the on-ramp vehicle enters into the control zone after a mainline vehicle; but the hierarchical control method works better when the on-ramp vehicle and a mainline vehicle enter into the control zone at the same time. Moreover, when the on-ramp vehicle starts from a low speed and the desired time gap is small or when mainline vehicles start from non-equilibrium states, the performance of the hierarchical control approach is better to improve traffic efficiency.

In the future, our research directions will move to scenarios where mainline vehicles may change lane to facilitate the merging of on-ramp vehicles.

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