Development of an Optimal Traffic Coordination System for Connected and Automated Vehicles

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Abstract: This paper presents a novel cyber-physical optimal vehicle coordination system for connected and automated vehicles (CAVs) on freeways. It is assumed that all vehicles are connected with the cloud-based computing system, where a vehicle coordination system optimizes the target trajectories of all vehicles for a smooth lane change or merging with a minimum deviation of speed. Coordination information is provided to individual vehicles that are equipped with local controllers and each of them determines the control acceleration to follow the target trajectories while maintaining a safe gap. For the vehicle coordination system, a new optimization scheme is proposed where the objective is to minimize the speed deviation and acceleration of all vehicles. The vehicles are divided into a few groups or platoons in the scheme, and their trajectories are successively optimized. The proposed coordination system is evaluated through numerical simulation.

Keywords: Cyber-physical system, connected and automated vehicles, successive optimization, vehicle coordination.

1. INTRODUCTION

The main concerns in road transportation systems are traffic congestion, fuel waste, pollution, and accidents. It is obvious that measures must be taken to reduce the burden of uncontrolled traffic growth for better living. It is expected that vehicle-to-others (V2X) communication technologies will be widely used, resulting in a connected vehicle environment (CVE). In V2X, various information (e.g., GPS position, speed) is shared between vehicles on the road, and better driving control can be achieved taking into account the surrounding conditions. Thus, a CVE may provide opportunities to achieve better coordinated vehicle flows in a road network.

Vehicles should consider the lane change requirements of others and cooperate in a complex driving context, in addition to their own driving efficiency [1, 2]. However, it is challenging to find an effective way to utilize vehicle information and develop a coordinated traffic management system. Various works attempted to overcome such challenges, e.g., Kamal et al. [3] proposed a novel cyber-physical multiagent framework to control traffic at an intersection in a CVE. It enables data communication between real traffic (cyber-network) and virtual traffic (physical-network). Such a framework applies not only to an intersection but also to others.

In a traffic network, lane change of vehicles has a significant influence on traffic safety and efficiency [4]. In congested situations, traffic flow is hindered by competition between vehicles as they make requests for lane changes and have difficulty finding a sufficient gap for a smooth lane change. Thus, vehicles are involved in fatal accidents that cost a lot to our society. Approximately 4% to 10% of road accidents were due to improper lane changes [5]. Lane changes on roads are identified as an important factor that influences the quality of traffic flows. Without providing a space dynamically for lane changing, vehicles may substantially increase travel delay, fuel consumption, and emissions in traffic. Coordinated traffic control is expected to alleviate these problems while also ensuring the safety and efficiency of lane changing vehicles. It is clear that improved control of lane changes through fully or semi-autonomous driving will lead to improved traffic flow.

There is a number of works for the lane change maneuver. Kesting et al. [6] proposed a general model that establishes lane change rules based on minimizing overall induced deceleration. Under this model, when a safety criterion is met, i.e., sufficient inter-vehicle gaps are available, the lane change is allowed. Li et al. [7] developed a method that a CAV platoon is reconfigured to a sufficient sparse formation and all lane changes are executed at the same time without collisions. The sparse formation is generated by widening the inter-vehicle gap via acceleration or deceleration. Kamal et al. [8] proposed a model predictive control framework to efficiently drive a vehicle on multi-lane roads in a connected vehicle environment, aiming at predictive lane changes to avoid a bottleneck. Although the above methods can improve individual driving performances, they still lack in ensuring smooth flows of all vehicles.

With motivation from the congestion phenomena of an actual road scenario due to uncoordinated lane changes and merging, this paper provides a futuristic solution for smooth and efficient flows of traffic by optimally coordinating vehicles for their timely lane changes. Specifically, we propose a novel cyber-physical vehicle coordination scheme on the freeway, assuming all vehicles are connected to the cloud-based computing system, where a coordination system optimizes the target trajectories of vehicles for a smooth lane change or merging at an interval of a few seconds. The individual vehicles, equipped with a local controller, receive such information to determine their precise control decisions at every short interval to follow the target trajectories. For real-time vehi-

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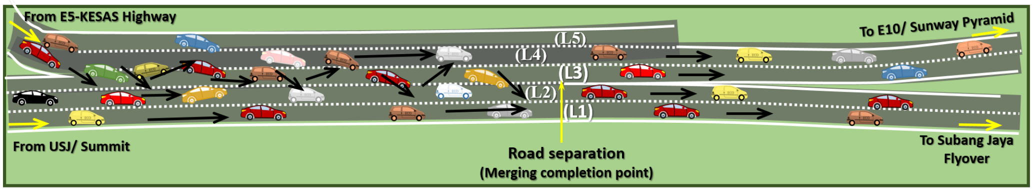


Fig. 1 Image of a real traffic scenario in Subang Jaya, Malaysia, where vehicles from two roads merge and divert in both ways in a short distance resulting huge congestion everyday.

cle coordination, a new optimization scheme is proposed, where the vehicles are divided into several small groups, and their trajectories are successively optimized using respective model predictive controllers. Numerical simulation reveals that vehicles are well-coordinateds, so an easy lane change is always possible.

2. COORDINATION SCHEME

The necessity of comprehensive traffic coordination can be understood from a real traffic network represented in Fig. 1, which shows how congestion is prevalent on the road called *Persiaran Kewajipan* in Subang Jaya, Malaysia. Vehicles from two roads merge and divert in both ways in a short distance resulting in huge congestion every day. More than half of the vehicles usually make multiple lane changes within about 300 m common sections before diverting into two different roads. As a vehicle cannot change lanes in a timely manner, it slows or stops, deteriorating the congestion. Such congestion can be overcome by optimally coordinating all vehicles for their timely arrival and lane changes.

It is assumed that the next-generation vehicles on the road are all CAV and connected with a cloud or edge computing system. The vehicles' state, target destination, and other information are assumed to be available in a cloud-based system. With such assumptions, a cyber-physical vehicle coordination system is proposed, where vehicles are divided into small groups, and their trajectories are successively optimized as shown in Fig. 2. Specifically, vehicles in each group are simultaneously optimized considering the safety constraint imposed by vehicles in the preceding group, and the optimization is repeated in a receding horizon mechanism. The optimal traffic coordination system plans how vehicles should change speed and where the vehicles should change lanes that keep the overall traffic performance optimum.

3. PROBLEM FORMULATION

We consider a two-lane road where most vehicles need to change lanes. At regular intervals, the coordination method divides all vehicles into some groups according to their sequences on the road, and each group is successively optimized. Since the process for each group of vehicles is the same, we focus on one of these groups in this study. Fig. 3 (a) shows an example with three vehicles, p1 and p2 on the left lane, and q1 on the right lane, that need coordination for smooth lane change by vehicle q1. Vehicle q1 has a request for lane change, but

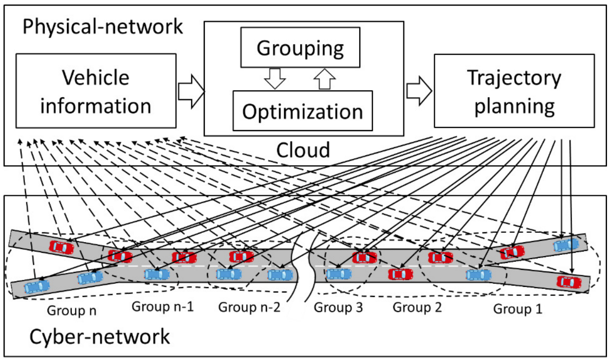
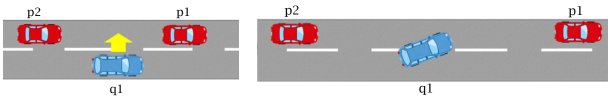


Fig. 2 Cyber-physical framework of a traffic network and the proposed cloud-based coordination system. The coordination is implemented by grouping the vehicles on roads and optimizing each group successively.



(a) (b)

Fig. 3 (a) a typical scenario for lane change cooperation request, and (b) expected scenario after coordination.

cannot change lane due to the low safety gap between p1 and q1. An example of expected solutions is shown in Fig. 3 (b). After receiving the request, both the p1 and p2 vehicles adjust their relative distance to allow the q1 vehicle to change lanes. However, depending on the relative positions and speeds of the vehicles, the expected solution may differ. A simple rule-based or hierarchical solution may not be efficient considering traffic performance. Therefore, optimal solutions are desired for all vehicles, which are described below.

3.1. Optimization Scheme

A discrete-time framework is considered with time step Δt. The motion of any vehicle $n \in \mathcal{N} = \{\mathrm{p1}, \mathrm{p2}, \ldots, \mathrm{q1}, \mathrm{q2} \ldots\}$ on either lane is given as

$$x_n(t + \Delta t) = x_n(t) + v_n(t)\Delta t, \tag{1}$$

$$v_n(t + \Delta t) = v_n(t) + a_n(t)\Delta t, \tag{2}$$

where x_n is the position and v_n is the velocity, a_n is the acceleration of the vehicle. Sudden acceleration and sudden braking are the cause of user discomfort. We set limits for vehicle acceleration and speed as follows.

$$a_{\min} \leq a_n(t) \leq a_{\max}, \tag{3}$$

$$v_{\min} \leq v_n(t) \leq v_{\max}. \tag{4}$$

where $a_{\min}$, $a_{\max}$, $v_{\min}$, and $v_{\max}$ are constants.

A safe distance between any leading vehicle $l \in \mathcal{N}$ and its following vehicle $f \in \mathcal{N}$ is necessary to avoid car collisions or uncomfortably aggressive braking, which is given indirectly using a nonlinear constraint such as

$$a_f(t) \leq a_{\mathrm{cfm}}(x_l(t),\ x_f(t),\ v_l(t),\ v_f(t)), \tag{5}$$

where a_{cfm} is calculated using a car following model. In this study, we choose a car-following model called the Intelligent Driver Model (IDM) [9], which is given as

$$a_{\mathrm{cfm}} = a_{\max}\left(1 - (v_f/v_{\mathrm{des}})^4 - (s/g)^2\right), \tag{6}$$

where $g = x_l - x_f - l$ denotes the gap $s = g_{\min} + v_f T + (v_f(v_f - v_l))/(2\sqrt{|a_{\max}\ a_{\min}|})$ denotes the desired gap, v_{des} is the desired velocity, l is the length of the leader, $g_{\min}$ is the minimum gap between the leader and the follower, T is the desired time headway.

3.1.1. Objective Function

The objective of the coordination is to provide sufficient gap to any lane-changing vehicle while keeping the speed deviation levels and acceleration of all vehicles minimum. Specifically, the objective function f_{cost} is given as

$$\begin{aligned} f_{\mathrm{cost}} = \sum_{h=1}^{H} \Bigg\{ & \sum_{n\in\mathcal{N}} \left(w_1(v_n(t) - v_{\mathrm{des}})^2 + w_2 a_n^2(t)\right) \\ & + \sum_{p\in\mathcal{P}}\sum_{q\in\mathcal{Q}} w_3(\theta_p + \theta_q)e^{-\alpha(x_p(t)-x_q(t))^2} \Bigg\}, \end{aligned} \tag{7}$$

where with $t = t_0 + h\Delta t$, $a_n = (v_n(t) - v_n(t-\Delta t)/\Delta t$ denotes the acceleration of vehicle n, $\mathcal{N}$ is the vehicle set in the partial optimization group, H is the time horizon, P, Q are the number of vehicles in the left and right lanes, respectively, $\theta_p, \theta_q \in \{0, 1\}$ is the binary variable that denotes the necessity to change the lane of vehicles. Value 1 of these binary variables denotes that a lane change is necessary, x_p, x_q are the position of vehicles on the left-lane, and on the right-lane, v_n is the velocity of each vehicle, and w_1, w_2, w_3 are weights. The first term of the objective function denotes the cost resulting from the speed deviation from v_{des}, and the second term means the acceleration cost. The third item expresses the lane change risk cost. The closer the distances between vehicles and lane-change ones are, the larger the cost is. Subject to the constraints described above, the objective function f_{cost} is minimized by choosing the appropriate speed for all vehicles.

The above optimization problem only coordinates the vehicle to create sufficient gaps when it lane change is necessary, and the lane change decision is actually made by each vehicle using the lane change model called Minimizing Overall Braking Induced by Lane Changes (MOBIL) [6]. Assuming that the states and destination (lane) of all vehicles are available, the above optimization problem is solved in the cloud for a group of vehicles considered in a subgroup. The target speeds and positions obtained from the optimization are then passed to the vehicles. Each of the vehicles considers its given target and uses its local controllers. The controller drives the vehicle safely until the next coordination step. In the next coordination step, the optimization is repeated in the cloud with newly available vehicle states.

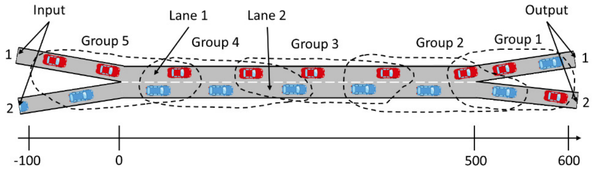


Fig. 4 Traffic network used for evaluation.

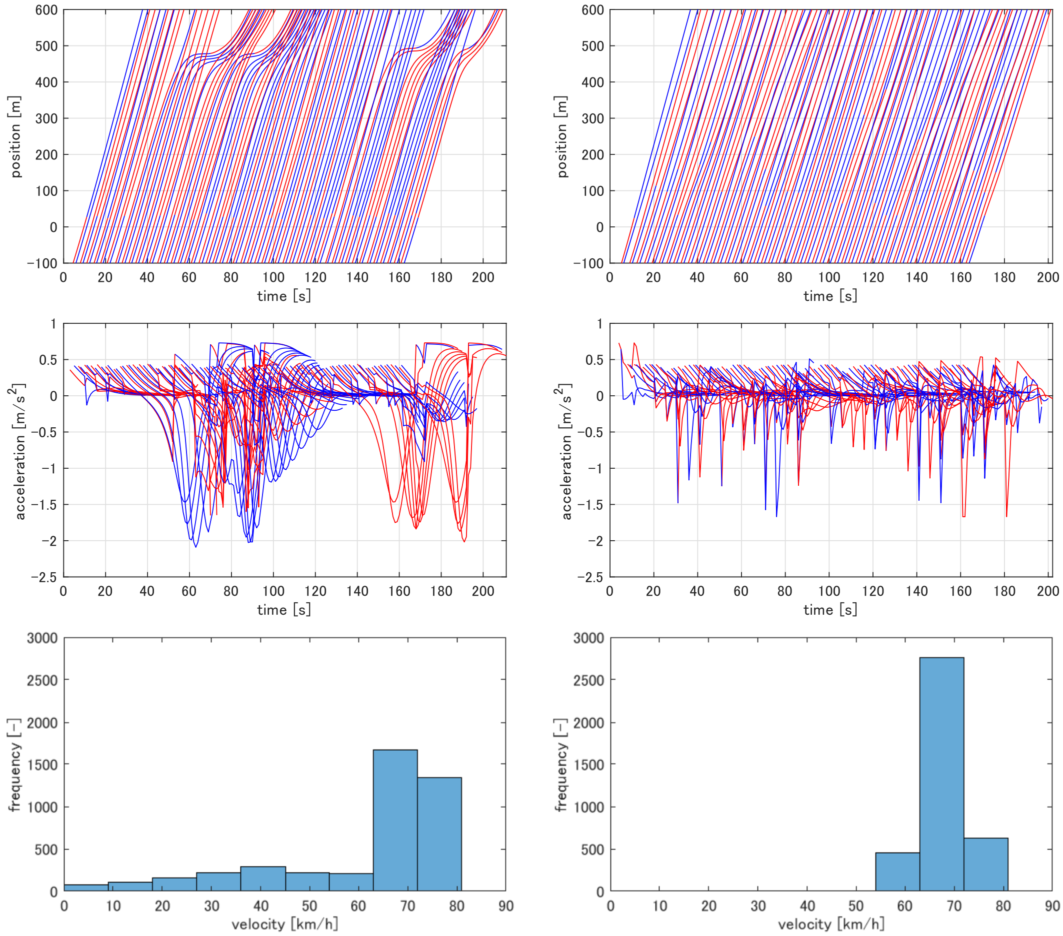
4. SIMULATION RESULTS

We perform a numerical simulation in MATLAB assuming the road in Fig. 4. Vehicles are inserted into the road at regular intervals. The roads 1 and 2 have a common section from 0 m to 500 m, where vehicles may change lanes depending on their destination. When vehicles with requests for lane change approach the junction, they slow down and wait for the right moment to change lanes. Then the vehicles in the other lane may also slow down to allow the waiting vehicles to. change lanes.For coordination, vehicles within the range of -100 m to 600 m are divided into several groups and optimized at every 5 s. For this optimization, we set the time step $\Delta t = 1$ s and the prediction horizon $T = 10$ s.

We simulate a traffic containing a total of 72 vehicles and observe their performances, e.g., the average velocity and total fuel consumption. The performances are compared for the case with and without the proposed coordination system. Fig. 5 (a) shows the vehicle trajectory, acceleration, and speed distributions of the vehicles, when they are controlled by human drivers without coordination. Often, some vehicles could not change lane in time and slow down by blocking others, resulting in congestion. Fig. 5 (b) shows the case when they are coordinated optimally using the proposed system, where traffic shows smooth performances as the could change the lane timely. The proposed coordination system reduces the fuel consumption and improves the average traffic speed significantly. It is found that for the traditional uncoordinated case, the total fuel consumption of all vehicles is 3186 ml, and the average speed is 57.15 km/h. In the case of coordinated traffic, the total fuel consumption becomes 2933 ml, and the average speed is 72.32 km/h. By reducing fuel consumption by 7.94% and improving the average speed by 26.54%, the proposed cyber-physical coordination scheme reveals potential for the future road transportation network.

5. CONCLUSION

Assuming a futuristic scenario of a CVE, we propose a novel cyber-physical vehicle coordination system to improve traffic flows on the freeway. Specifically, a coor-



(a) Traditional traffic (b) Coordinated traffic

Fig. 5 Evaluation results in terms of trajectories, acceleration, ans speed distribution of vehicles.

dination system optimizes groups' target trajectories successively for a smooth lane change or merging. The numerical simulation results confirm the computation efficiency of the coordination scheme for real-time implementation. Furthermore, vehicles smoothly could find a state in which a required vehicle could change lane immediately. As the local controller executes driving decisions, the safety concerns are also eliminated. It shows that the proposed traffic coordination system for overall coordination is feasible and useful.

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