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Distributed Consensus-Based Cooperative Highway On-Ramp Merging Using V2X Communications

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Abstract

Highway on-ramp merging is considered as one of the main factors that causes traffic congestion on highways. The drivers along the on-ramp need to adjust vehicle speeds and positions to enter the highway, while the drivers on the highway should also carefully accommodate vehicle speeds and positions to avoid collision with the merging vehicles from the on-ramp, which heavily affects upstream traffic flows. In congested traffic conditions, such maneuvers if inefficiently performed will lead to high risks of accidents and excessive energy consumption and pollutant emissions. In this work, we present an innovative approach to this scenario, where distributed consensus protocol is developed for Connected and Automated Vehicles (CAV) to cooperate with each other by using Vehicle-to-X (V2X) communications. A Road Side Unit (RSU)-equipped infrastructure installed in the merging area can receive vehicles' information from both the highway and the on-ramp using Vehicle-to-Infrastructure (V2I) communications, and assign vehicles with sequence identifications based on their estimated arrival time at the merging area. Then vehicles apply distributed consensus protocol to adapt their speeds and positions to the preceding vehicles (either physical ones on the same lane or "ghost" ones projected from the other lane) with Vehicle-to-Vehicle (V2V) communications. After vehicles along the on-ramp merge into the highway, a new vehicle string (either tightly-coupled or loosely-coupled) is created. A comprehensive simulation study is conducted, and system-wide benefits in terms of traffic throughput and energy saving are also demonstrated in the work.

Introduction

Our transportation systems around the world have been developed at an especially fast pace recently, since they are necessary conditions for different countries and regions to reach the economic prosperity. It is estimated that there are more than 1 billion motor vehicles worldwide now, and this number will be doubled within one or two decades [1]. Intensive transportation activities have led to a variety of social and economic issues. For instance, on the safety perspective, it was reported that the number of people perished from car accidents on US highways is larger than 30,000 every year [2]. On the efficiency perspective, it was estimated that there were 3.1 billion gallons of fuel wasted worldwide due to traffic congestion in 2014, which approximately equated to 19 gallons per commuter [3].

Connected and Automated Vehicle (CAV) technology is considered as one of the primary breakthroughs to address aforementioned issues. Connected Vehicle (CV) adopts different communication technologies to communicate with the driver, other vehicles on the road (through Vehicle-to-Vehicle, i.e., V2V), roadside infrastructure (through Vehicle-to-Infrastructure, i.e., V2I), and the "Cloud" [4]. Automated Vehicle (AV) uses a variety of methodologies (e.g., radar, LiDAR, computer vision) to detect its surroundings and therefore has the capability to be driven without direct driver input of controlling the steering, acceleration, and braking. CAV takes advantage of both CV and AV, leveraging connectivity and automation. It can not only operate in isolation from other vehicles using internal sensors, but also communicate with nearby vehicles and infrastructure to make decisions in a cooperative manner.

Researchers around the world have been developing various CAV applications to address traffic-related issues and improve efficiency and safety in specific traffic scenarios, such as highway on-ramp merging. Ramp metering has been considered as a popular application to regulate the upstream traffic flows on on-ramps. A variety of control protocols have been proposed so far, including nonlinear optimal control [5, 6, 7], feedback control [8, 9, 10], and some heuristic control protocol [11, 12, 13]. However, since ramp metering will introduce a stop-and-go maneuver, which leads to extra energy consumption and pollutant emissions, many have developed advanced technology to address this issue. An optimal linear feedback system was proposed by Levine *et al.* [14] to regulate the position and speed of every vehicle in a densely packed string of vehicles. Awal *et al.* [15] proposed a proactive optimal merging strategy to computes the optimal merging order for the group of vehicles of the two streams (main road and on-ramp), which outperforms the conventional mainstream priority merging in terms of energy consumption, traffic flow, average speed, and merging time and rate. Milanes *et al.* [16] presented a fuzzy-logic approach for vehicles to merging from a minor to a major road in congested traffic situations, which allows merging vehicles to enter the major road fluidly to avoid congestion on the minor road, and modifies the speed of the vehicles already on the major road to minimize the effect on that already congested major road. Marinescu *et al.* [17] proposed a slot-based merging algorithm which enables cooperation between vehicles on the main road and on the on-ramp to achieve a highly efficient merging. Ntousakis *et al.* [18] proposed a cooperative merging system based on Vehicle-to-X (V2X) communications, and adopted a microscopic traffic simulator to evaluate its performance and impact on highway capacity. Cao *et al.* [19] used a Model Predictive Control (MPC) scheme to propose a cooperative merging path generation method for vehicles to merge smoothly on the main road.

One of the advantages that CAVs have is that they can provide shorter time headway and quicker responses while improving highway capacity by identifying appropriate target speeds [20]. Forming platoons or strings of vehicles travelling at high speeds, accelerating or braking simultaneously, has been a popular approach to solve traffic congestion problem. Specifically, the Cooperative Adaptive Cruise Control (CACC) system has been considered as a promising CAV application. The main advantages of a CACC system are: a) connected and automated driving is safer than human driving since it minimizes driver distractions; b) roadway capacity is improved due to the reduction of time headways; c) energy consumption and pollutant emissions are reduced due to the reductions of both unnecessary acceleration maneuvers and aerodynamic drag on the vehicles in the platoon [21]. During the recent years, numerous research works have been conducted to study different aspects of the CACC system [22, 23, 24, 25, 26, 27, 28, 29].

Applying the technology of the CACC system to highway on-ramp merging scenario can be considered as an efficient solution to the traffic congestion issue on highways. The basic idea is to organize vehicles into platoons or strings with the objective of maximizing roadway capacities and traffic flow. Lu *et al.* [30] proposed a real-time merging control algorithm that calculates a smooth reference speed trajectory for the on-ramp merging vehicles based on the speed of the main lane vehicles. Dao *et al*. [31] proposed a distributed control strategy to assign vehicles into platoons in the merging scenario, and select lanes for platoons using V2V communications. Some of other CACC-related control concepts for facilitating on-ramp merging have been reviewed in [32].

In the rest of this paper, we first demonstrate the proposed methodology for the highway on-ramp merging, which includes a statement of the system assumptions, an illustration of the system architecture, a demonstration of the vehicle sequencing protocol, and an introduction of the distributed consensus-based cooperative merging maneuver. Next, a simulation study is shown, where the microscopic traffic simulator VISSIM [33] is used to model the traffic network and the proposed protocol, MATLAB [34] is used to analyze the simulation results derived from VISSIM, and MOtor Emission Simulator (MOVES) [35] is used to evaluate the energy consumption and pollutant emissions of the simulation. Finally, we draw the conclusions of this work, and point out some future steps that we might look into.

Methodology

In this section, we will focus on the specific methodology proposed for the highway on-ramp merging system. The methodology is broken down into four separate parts: a) System assumptions, which states the specifications we made while modelling this system; b) System architecture, which shows a general picture of this system; c) Vehicle sequencing protocol, which demonstrates the developed protocol to assign merging vehicles with Sequence IDentification (SID) numbers; 4) Distributed consensus-based cooperative merging, which acts as the longitudinal controller to coordinate different vehicles' maneuvers for highway on-ramp merging.

System Assumptions

It shall be noted that since our study mainly focuses on designing highway on-ramp merging protocol, some reasonable specifications are made while modelling the system to enable the theoretical analysis:

a) All vehicles in this study are able to get their precise information (i.e., positions, speeds, accelerations, etc.) by their equipped sensors, such as Inertial Measurement Unit (IMU), On-Board Diagnostic (OBD) system, and high-precision GPS.
b) All vehicles in this study are CAVs with the ability to share information with each other through V2V communications, and share information with the infrastructure through V2I communications.
c) Only the rightmost lane of highway is taken into account for on-ramp merging, and the on-ramp only has one lane.
d) No lane change maneuver is conducted on the rightmost lane of highway after vehicles enter the V2I communication range, and before vehicles reach the merging lane.
e) Only the longitudinal control is considered in this study, while default lane change models are used for the lateral control.

System Architecture

The proposed highway on-ramp merging system takes advantage of V2X communications, which means that both V2V communications and V2I communications are used. As for the V2V communications, CAVs can obtain their own information from appropriate sensors, and share them with other CAVs in the Vehicular Ad-Hoc Network through Dedicated Short Range Communication (DSRC). As for the V2I communications, CAVs can share their information with RSU-equipped infrastructures, while those infrastructures can also share Geographic Information System (GIS) and SID information with CAVs through DSRC.

The overall system architecture can be illustrated by Figure 1. When merging vehicles (on the on-ramp and the rightmost lane of highway) enter the V2I communication range of the RSU-equipped infrastructure located near the highway on-ramp merging area, they send their own information to the infrastructure. The computer connected to the infrastructure calculates the estimated arrival time to the merging point for each vehicle. After combining the estimated arrival time information from other vehicles, the infrastructure returns a SID to each vehicle approaching the merging point by applying the vehicle sequence protocol.

Next, each vehicle on either the on-ramp or the rightmost lane of highway connects to its predecessor based on their SIDs. The predecessor of a vehicle can be either on the same lane with this vehicle, or on the other lane (which can be projected on the same lane). The distributed consensus-based algorithm can then be applied to vehicles to form strings before reaching the merging point.

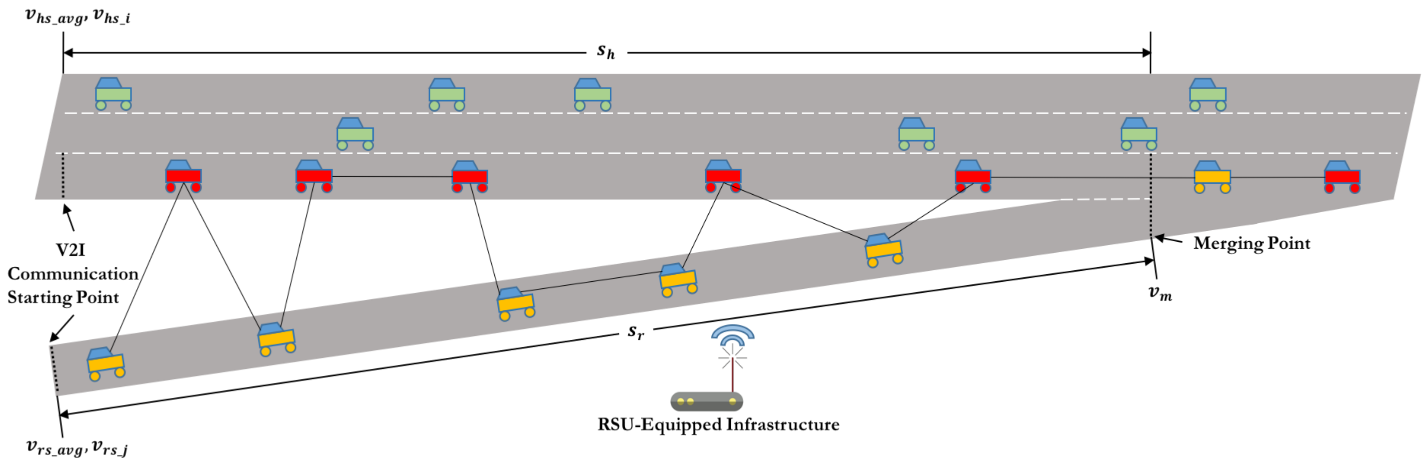

Figure 1. An illustration of the distributed consensus-based cooperative highway on-ramp merging system architecture.

Vehicle Sequencing Protocol

The vehicle sequencing protocol is designed to arrange vehicles with a predefined sequence, so they can cooperate with each other before merging, avoiding high risks of collisions and excessive energy consumption and pollutant emissions upon reaching the merging point. This protocol can be broken down into three procedures: a) Calculation of the maximum reachable speed of on-ramp vehicles; b) Calculation of the estimated arrival time; c) Assignment of vehicle sequence identification.

Parameters used in this protocol are defined in two groups below. Parameters in the first group are directly measurable by vehicles or infrastructures, therefore are assumed to be known:

s_h — Distance on the rightmost lane of highway from the V2I communication starting point to the merging point;

s_r — Distance on the on-ramp from the V2I communication starting point to the merging point;

v_{lim} — Highway speed limit;

v_{hs_i} — Speed of vehicle i when reaching the V2I communication starting point on the rightmost lane of highway;

v_{hs_avg} — Average speed of vehicles when reaching the V2I communication starting point on the rightmost lane of highway during the past time window $[0, t_{window}]$;

v_{rs_j} — Speed of vehicle j when reaching the V2I communication starting point on the on-ramp;

v_{rs_avg} — Average speed of vehicles when reaching the V2I communication starting point on the on-ramp during the past time window $[0, t_{window}]$;

a_{max} — Maximum acceleration of vehicles without compromising safety and comfort.

When vehicles reach the V2I communication starting point on both the rightmost lane of highway and the on-ramp, they send their speed information to the RSU-equipped infrastructure. Therefore, the infrastructure can calculate average speeds of vehicles reaching both points (v_{hs_avg}, v_{rs_avg}) during the past time window $[0, t_{window}]$, which reflect recent traffic conditions on both lanes.

Parameters in the second group are not directly measurable by vehicles or infrastructures, and they can be calculated by the methods demonstrated later in this section:

t_{acc} — Minimum time spent by on-ramp vehicles accelerating from v_{rs_avg} to v_{lim};

s_{acc} — Distance travelled by on-ramp vehicles accelerating from v_{rs_avg} to v_{lim};

v_{rm_max} — Maximum reachable speed of on-ramp vehicles when reaching the merging point;

t_{r_min} — Minimum reachable time spent by vehicles on the on-ramp;

t_{h_i} — Estimated time spent by vehicle i travelling the distance of s_h;

t_{r_j} — Estimated time spent by vehicle j travelling the distance of s_r;

t_{head_safe} — Safety time headway;

t_{head_V2V} — V2V connection time headway;

v_m — Estimated merging speed.

Maximum Reachable Speed of On-Ramp Vehicles

Vehicles coming from arterials to highways are most likely to accelerate while travelling through the on-ramp, therefore we want to calculate the maximum reachable speed of on-ramp vehicles based on known parameters. Since the highway speed limit v_{lim} is assumed to be known, we can calculate the minimum reachable time spent by on-ramp vehicles accelerating from v_{rs-avg} to v_{lim} as

$$t_{acc} = \frac{v_{lim} - v_{rs-avg}}{a_{max}} \tag{1}$$

Therefore, this accelerating distance is

$$S_{acc} = \frac{(v_{rs-avg} + v_{lim})t_{acc}}{2} = \frac{{v_{lim}}^2 - {v_{rs-avg}}^2}{2a_{max}}$$

(2)

The on-ramp calculation process can then be divided into two different cases based on this acceleration process.

a) $s_r < s_{acc}$

This case means that on-ramp vehicles cannot accelerate to highway speed limit v_{lim} before merging, which most likely to happen when the on-ramp is short. We can calculate the maximum reachable speed based on Figure 2.

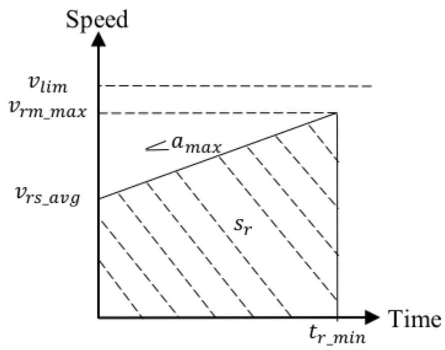

Figure 2. Maximum reachable speed of on-ramp vehicles when reaching the merging point without accelerating to highway speed limit.

The maximum reachable speed of on-ramp vehicles when reaching the merging point can be derived as

$$v_{rm\_max} = v_{rs\_avg} + a_{max}t_{r\_min}$$

(3)

And based on Figure 2, we can get the following equation

$$s_r = \frac{(v_{rs\_avg} + v_{rm\_max})t_{r\_min}}{2}$$

(4)

Therefore, combining equation (3) and (4), the following variables can be derived as

$$t_{r\_min} = \frac{-v_{rs\_avg} + \sqrt{{v_{rs\_avg}}^2 + 2a_{max}s_r}}{a_{max}}$$

(5)

$$v_{rm\_max} = \sqrt{{v_{rs\_avg}}^2 + 2a_{max}s_r}$$

(6)

b) $s_r > s_{acc}$

This case means that on-ramp vehicles can accelerate to highway speed limit v_{lim} before merging. The vehicle speed trajectory can be illustrated by Figure 3. In this case, the maximum reachable speed of on-ramp vehicles is

$$v_{rm\_max} = v_{lim}$$

(7)

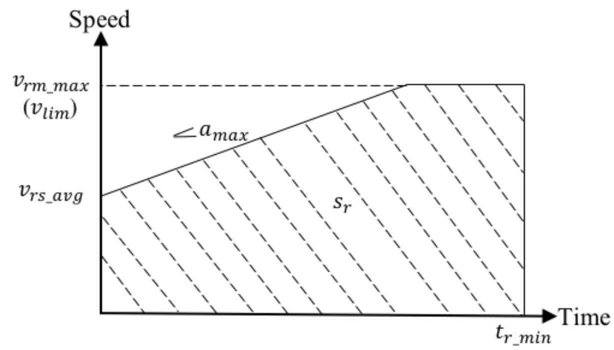

Figure 3. Maximum reachable speed of on-ramp vehicles when reaching the merging point with highway speed limit.

Estimated Arrival Time

The estimated arrival time is calculated to assign SID to each vehicle in the system. Since it is estimated before a vehicle actually travels to the merging point, the result may vary from the actual arrival time. However, since the actual arrival time of vehicles usually vary by relatively large values based on the errors we introduce, the estimated values we calculate are already effective enough to be sorted in order of time.

Since the values of v_{rm_max} can be calculated by known parameters for both cases above, we can categorize the calculation of vehicle estimated arrival time into two scenarios, and set the estimated merging speed v_m to be the lower one of v_{hs_avg} and v_{rm_max}. The reason we consider the average speed of highway vehicles but the maximum reachable speed of on-ramp vehicles is that on-ramp vehicles are supposed to accelerate on the on-ramp, but highway vehicles are more likely to maintain rather stable speeds in a short segment.

a) If $v_{hs\_avg} \leq v_{rm\_max}$, then $v_m = v_{hs\_avg}$

Since the merging speed is set to v_{hs_avg}, we can derive the estimated time spent by vehicle i travelling the distance of s_h on the rightmost lane of highway by

$$t_{h\_i} = \frac{s_h}{v_{hs\_i}}$$

(8)

In this case, since on-ramp vehicles reach v_{hs_avg} before merging, the speed trajectory of vehicle j has the same shape as in Figure 3 (though parameters in the figure are different). We can derive estimated time spent by vehicle j travelling the distance of s_r on the on-ramp by

$$t_{r\_j} = \frac{2a_{max}s_r + (v_{hs\_avg} - v_{rs\_j})^2}{2a_{max}v_{hs\_avg}}$$

(9)

b) If $v_{hs-avg} > v_{rm-max}$, then $v_m = v_{rm-max}$

Since the merging speed is set to v_{rm-max}, based on Figure 4, we can derive the estimated time spent by vehicle i travelling the distance of s_h on the rightmost lane of highway by

$$t_{h\_i} = \frac{2a_{max}(s_h - s_r) - ({v_{hs\_i}}^2 + {v_{rs_{avg}}}^2) + 2v_{hs\_i}\sqrt{{v_{rs\_avg}}^2 + 2a_{max}s_r}}{2a_{max}\sqrt{{v_{rs\_avg}}^2 + 2a_{max}s_r}}$$

(10)

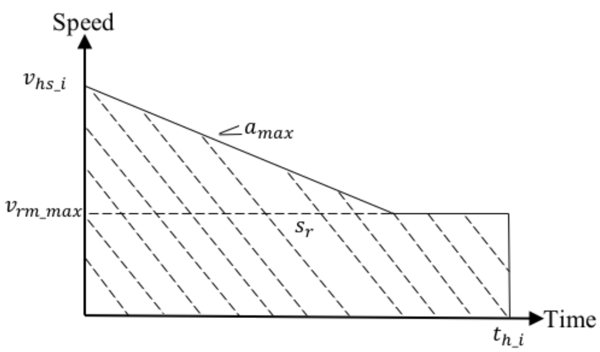

Figure 4. Deceleration process of vehicle i travelling the distance of s_h on the rightmost lane of highway.

In this case, since on-ramp vehicles do not reach v_{hs_avg} before merging, the speed trajectory of vehicle j has the same shape as in Figure 2 (though parameters in the figure are different). Since the merging speed is set to be the same as v_{rm-max}, we can derive estimated time spent by vehicle j travelling the distance of s_r on the on-ramp by

$$t_{r\_j} = \frac{-v_{rs\_j} + \sqrt{{v_{rs\_j}}^2 + 2a_{max}s_r}}{a_{max}}$$

(11)

Once the estimated time spent by each vehicle travelling through the V2I communication area is calculated, the estimated arrival time at the merging point can be easily get by adding the estimated spending time (t_{h_i} or t_{r_j}) to the current time while vehicle i or vehicle j reaches the V2I communication starting point. Different from estimated spending time, which is a time segment (e.g., 10.5 s), the estimated arrival time is the time of day (e.g., 15:08:10:5).

Vehicle Sequence Identification

Since the estimated arrival time is calculated based on different vehicles' speeds when reaching the V2I communication starting point (v_{hs_i} and v_{rs_j}), it is possible that the estimated arrival time of a follower is earlier than its predecessor on the same lane. In that case, the estimated arrival time of the follower is defined as t_{head_safe} later than the estimated arrival time of the predecessor. If a highway vehicle and an on-ramp vehicle have the same estimated arrival time, then the estimated arrival time of the on-ramp vehicle is defined as t_{head_safe} later than that of the highway vehicle.

Upon receiving the estimated arrival time of every vehicle in the V2I communication area, the infrastructure sorts vehicles in the network in order of time, and assign them with consecutive SIDs.

Distributed Consensus-Based Cooperative Merging Protocol

Once vehicles are assigned with different SIDs, they are allowed to connect with others through V2V communications, and then apply the distributed consensus algorithm to merge in a cooperative manner. The general protocol for vehicle k (can either be a highway vehicle or on-ramp vehicle) is proposed below.

Input: estimated arrival time and SID of vehicle k (T_k, n_k) and other vehicles in communication range
Output: acceleration of vehicle k

if a vehicle p with SID ($n_p = n_k - 1$) has its estimated arrival time satisfy ($T_k - t_{head\_V2V} \leq T_p \leq T_k$)
  if vehicle p is on the same lane with vehicle k
    Vehicle p becomes the physical predecessor of vehicle k;
    Acceleration of vehicle k is calculated by *Algorithm 1*;
  else
    Vehicle p becomes the "ghost" predecessor of vehicle k;
    Acceleration of vehicle k is calculated by *Algorithm 2*;
  end
else
  Acceleration of vehicle k is calculated by the default car following model;
end

The reason vehicle k only connects to a physical or "ghost" predecessor within a certain time range (t_{head_V2V}) is that, if the estimated arrival time of two vehicles vary by much, vehicle k tends to catch up with its predecessor in an aggressive way to form a string, leading to excessive energy consumption and pollutant emissions. However, vehicle k can proceed with the default car following model, acting as an individual vehicle without forming a string with others. This case most likely to happen when the traffic flow of highway is low.

As for the "ghost" predecessor, since vehicle k is able to receive information from vehicle p through V2V communications despite they are not on the same lane, the acceleration of vehicle k can be calculated based on the movement of vehicle p. In a more intuitive explanation, vehicle p is projected in front of vehicle k, so vehicle k can adjust its speed and position to follow the "ghost" vehicle p all the way until they physically merge. The algorithm used in this distributed consensus-based cooperative merging protocol can be proposed below.

Algorithm 1. Distributed consensus algorithm for physical predecessor-follower.

$$a_k = -\delta[(s_k - s_p + s_{head}) + \gamma(v_k - v_p)]$$

(12)

a_k is the acceleration of vehicle k; δ and γ are tuning coefficients; s_k is the relevant position of vehicle k to the merging point; s_p is the relevant position of vehicle p to the merging point; v_k is the longitudinal speed of vehicle k; v_p is the longitudinal speed of vehicle p. $s_{head} = \min(v_p t_{head_{safe}}, s_{head\_safe})$ is the desired distance headway, where t_{head_safe} is the safety time headway and s_{head_safe} is the safety distance headway. The reason we set s_{head_safe} as a constraint of s_{head} is that when the speed of the preceding vehicle becomes very low (i.e., $v_p \to 0$), the term $v_p t_{head_{safe}}$ cannot guarantee the safety distance headway between two vehicles.

In this algorithm, the part $(s_k - s_p + s_{head})$ is the position consensus term, where vehicle k and vehicle p tend to maintain a distance headway of s_{head}. When $\|s_k - s_p\| \to s_{head}$, these two vehicles reach position consensus. The part $(v_k - v_p)$ is the speed consensus term, where vehicle k and vehicle p tend to maintain the same speed. When $\|v_k - v_p\| \to 0$, these two vehicles reach speed consensus. The acceleration of vehicle k is calculated based on these two consensus term, leading vehicle k to consensus with its physical predecessor vehicle p.

Algorithm 2. Distributed consensus algorithm for "ghost" predecessor-follower.

$$a_k = -\alpha\delta\left[\left(s_k - s_p + v_m t_{head\_safe}\right) + \gamma\left(v_k - v_p\right)\right] - \beta(v_k - v_m) \tag{13}$$

Compared to *Algorithm 1*, there are three new variables in *Algorithm 2*, where α and β are tuning coefficients, and v_m is the estimated merging speed. In the position consensus part $(s_k - s_p + v_m t_{head\_safe})$, v_m is used to calculate the distance headway without setting a constraint, since v_m is high enough to guarantee safety distance headway between two vehicles. And because vehicle p acts as the "ghost" predecessor of vehicle k, where two vehicles come from different lanes and normally have a relatively big difference in initial speeds, the distance headway is calculated based on the merging speed v_m. Therefore, $v_m t_{head\_safe}$ will maintain a constant value which causes less disturbances for vehicle k, until vehicle k and vehicle p physically merge at the merging point. In addition, we also set another speed consensus term $\beta(v_k - v_m)$ in *Algorithm 2*, allowing vehicle k to reach consensus with the merging speed v_m while attenuating the disturbance brought by speed consensus term $\gamma(v_k - v_p)$.

Simulation Study

In this section, we conduct simulation study of the proposed system by using multiple simulation software. The microscopic traffic simulator VISSIM is used to build the traffic network and integrate the proposed protocol. MATLAB is used to analyze the results got from VISSIM. MOVES is used to evaluate the energy consumption and pollutant emissions of vehicles.

Specifically, we build our simulation network based on University of California, Riverside (UCR) campus area. We mainly focus on the on-ramp from University Ave to Moreno Valley Freeway/Escondido Freeway (CA-60 E/I-215 S). This is one of the busiest on-ramp in Riverside County, California where numerous vehicles merge to the highway during the afternoon peak hours. The simulation network built in VISSIM is shown as Figure 5. The longer yellow segment is the rightmost lane of highway, which has a distance of 1283.29 m, while the shorter yellow segment is the on-ramp, which has a distance of 415.40 m. The proposed RSU location is illustrated in the figure, where the DSRC radius of the RSU covers the 745 m V2I communication distance on the highway, and the 415 m V2I communication distance on the on-ramp.

As aforementioned system assumptions, in this simulation, we only consider the rightmost lane of Moreno Valley Freeway/Escondido Freeway for on-ramp merging, and the on-ramp only has one lane. The merging action is merely conducted by vehicles travelling on these two lanes, and only the longitudinal control is considered in this study, while default lane change models are used for the lateral control. The network and vehicle parameters of both scenarios in the simulation study are set in Table 1.

Table 1. Network and vehicle parameters of both scenarios in the simulation study.

Distance on the highway from the V2I communication starting point to the merging point s_h	745 m
Distance on the on-ramp from the V2I communication starting point to the merging point s_r	415 m
Distance travelled by vehicles on the highway	1285 m
Distance travelled by vehicles on the on-ramp	955 m
Highway speed limit v_{lim}	30 m/s
Maximum acceleration of vehicles a_{max}	3 m/s^2
Safety time headway t_{head_safe}	0.8 s
Safety distance headway s_{head_safe}	3 m
Time window t_{window}	30 s
Merging speed of vehicles v_m	30 m/s
Simulation time step	0.1 s
Tuning coefficients δ	1
Tuning coefficients γ	15
Tuning coefficients α	0.005
Tuning coefficients β	0.995

It needs to be noticed that, in this simulation network, the RSU-equipped infrastructure can be installed near the midpoint of s_h along the highway, which typically has a 500-m V2I communication radius at least [36]. Although vehicles travel more than 1000 m (diameter of the V2I communication circle) on the highway, the communicate with the infrastructure is only conducted within the range of s_h. The reason we allow vehicles to travel such a long distance is to better study the effect of the proposed protocol on the traffic network.

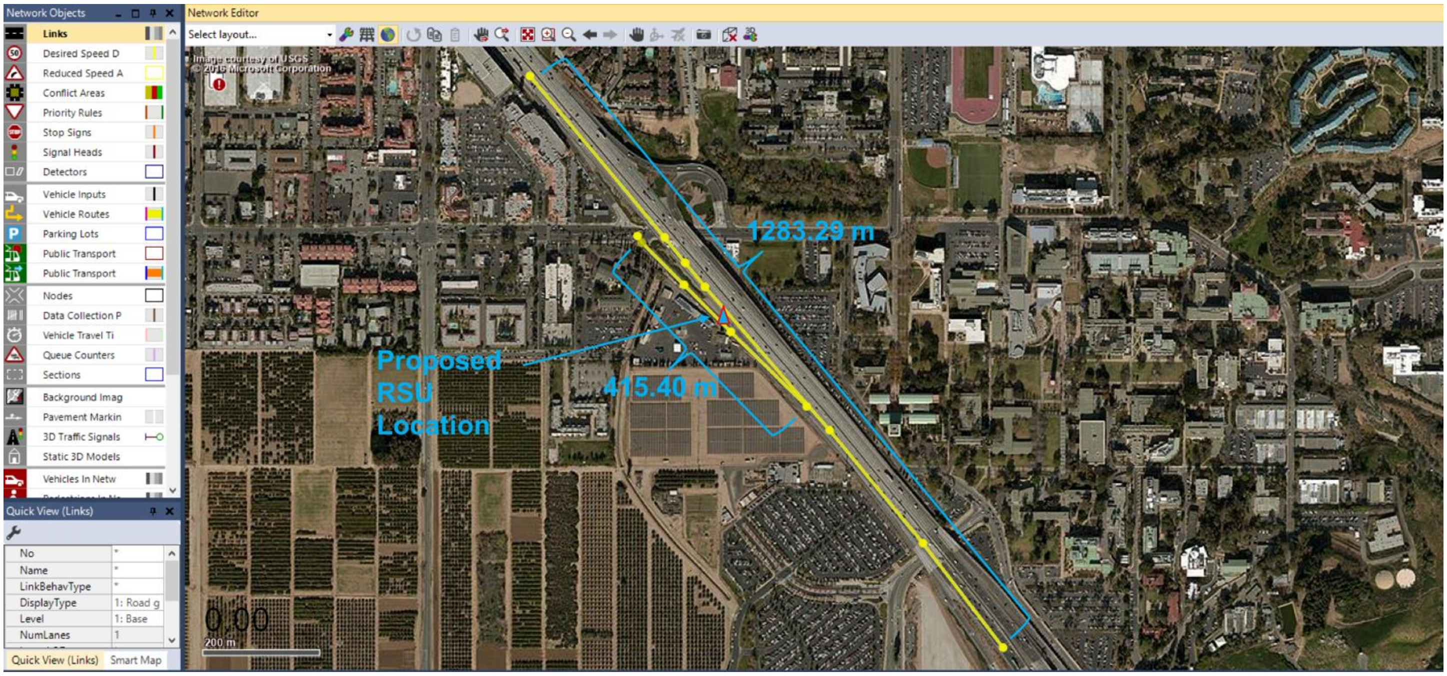

Figure 5. Vissim GUI view of the traffic simulation network based on the on-ramp from University Avenue to Moreno Valley Freeway/Escondido Freeway (CA-60 E/I-215 S).

Scenario 1: Lower Traffic Flow

In this scenario, we study the effect of our proposed protocol on the traffic simulation network with relatively lower traffic flows. We randomly pick 10 vehicles with consecutive SIDs from the traffic flow, and analyze their speed trajectories for both cases: one uses baseline model and another uses the proposed protocol. It turns out to be that 7 highway vehicles and 3 on-ramp vehicles form these 10 vehicles. The speed results are shown in Figure 6 and Figure 7.

As can be seen from both figures, these 7 highway vehicles are marked as “Veh.h1” to “Veh.h7”, and 3 on-ramp vehicles are marked as “Veh.r1” to “Veh.r3”. Different vehicles enter and exit the traffic simulation network at different time, and their initial speeds are different while within certain ranges. In the case of the baseline model shown in Figure 6, all vehicles tend to suffer from rapid speed changes when reaching the merging point, since they can only adjust their speed with vehicles on the other lane when they are close to the merging point. Highway vehicles seems to decelerate significantly to create gaps for on-ramp vehicles to merge.

However, in the case of the proposed protocol shown in Figure 7, highway vehicles adjust their speeds and longitudinal positions in advance. After vehicles reach the V2I communication starting point, the highway vehicles adjust their speeds and positions based on the assigned SIDs, and form a 7-vehicle string (maybe there are more vehicles in the string since we only consider these 10 vehicles in this scenario). Meanwhile, another string is also formed on the on-ramp. When vehicles reach the merging point, they also reach consensus with vehicles from the other lane. Vehicles coming from both lanes share the same speed (merging speed v_m), and gaps have already been created for on-ramp vehicles to merge. The default lane change model in VISSIM is applied to on-ramp vehicles, enabling them to change lane to the left without adjusting longitudinal speeds and positions. After all 10 vehicles finish merging maneuvers, these two strings merge to a single string on the rightmost lane of highway. From the first vehicle to the last vehicle in the string, the SIDs of them are in an ascending order.

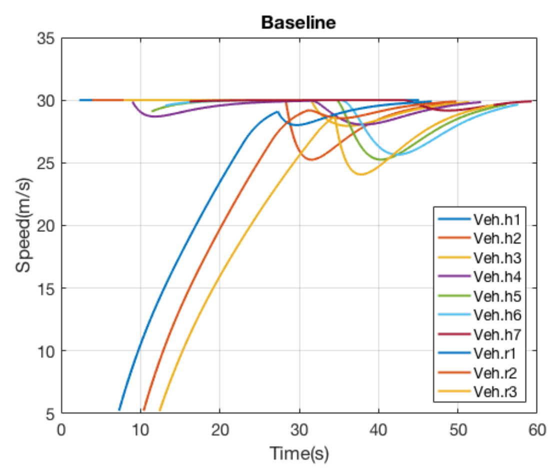

Figure 6. Speed trajectories of 10 vehicles (7 from highway and 3 from on-ramp) by applying the baseline model.

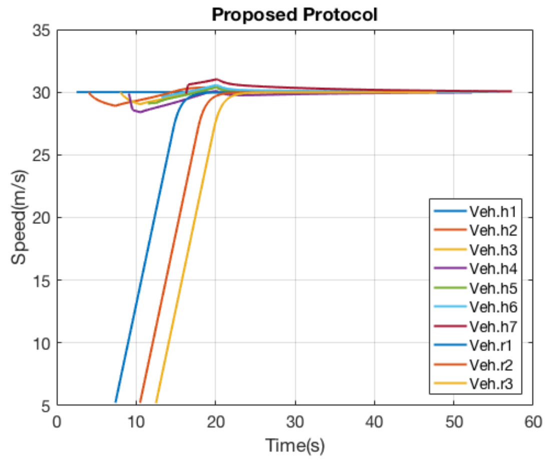

Figure 7. Speed trajectories of 10 vehicles (7 from highway and 3 from on-ramp) by applying the proposed protocol.

After the MOVES model has been adopted to perform the multiple scale analysis on the environmental impacts of the proposed protocol together with the baseline model, the results are demonstrated in Table 2.

Table 2. Simulation results of scenario 1.

	Travel Time (s)	Speed (m/s)	CO (g)	NOx (g)	CO_2 (g)	Energy (KJ)
Baseline	42.77	29.02	1.37	0.32	270.36	3759.39
Proposed Protocol	40.49	30.02	1.36	0.31	269.99	3746.20
Improved	5.33%	3.44%	0.73%	3.13%	0.51%	0.36%

We analyze the average travel time and the average speed of all these 10 vehicles during the periods that they are travelling in our traffic simulation network. We also calculate the average produced emission and consumed energy while each vehicle is travelling in this network. As shown in Table 2, the proposed protocol improves the average travel time and the average speed by 5.33% and 3.44%, respectively, compared to the baseline. It also reduces the energy consumption by 0.36%, and the pollutant emission by up to 3.13%.

Scenario 2: Higher Traffic Flow

In this scenario, we study the effect of our proposed protocol on the traffic simulation network with relatively higher traffic flows. Similar to scenario 1, we still randomly pick 10 vehicles with consecutive SIDs from the traffic flow, which turns out to be 6 highway vehicles and 4 on-ramp vehicles. We analyze their speed trajectories for both cases: one uses baseline model and another uses the proposed protocol. The results are shown in Figure 8 and Figure 9.

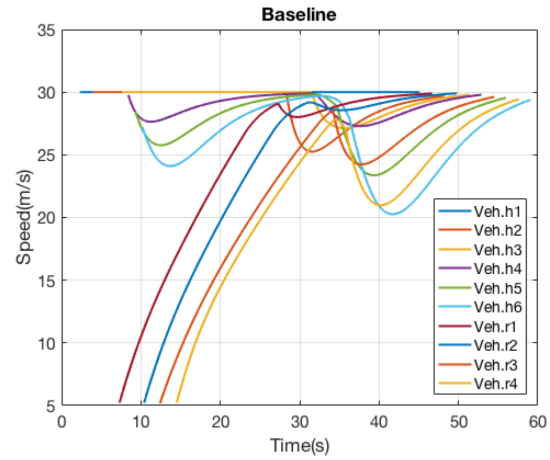

Figure 8. Speed trajectories of 10 vehicles (6 from highway and 4 from on-ramp) by applying the baseline model.

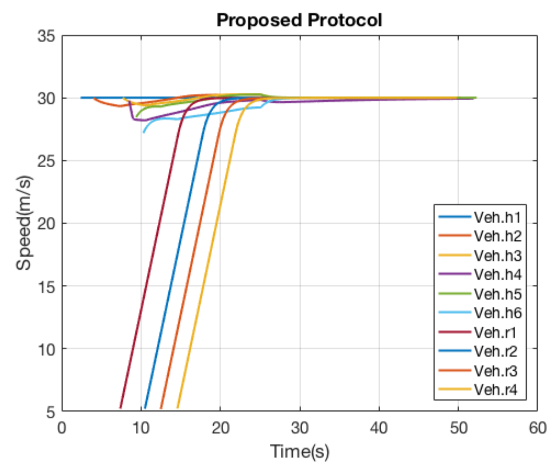

Figure 9. Speed trajectories of 10 vehicles (6 from highway and 4 from on-ramp) by applying the proposed protocol.

As can be seen from both figures, these 6 highway vehicles are marked as “Veh.h1” to “Veh.h6”, and 4 on-ramp vehicles are marked as “Veh.r1” to “Veh.r4”. In the baseline model case shown in Figure 8, the maneuver that highway vehicle 4, 5, and 6 all decelerate at an early stage is caused by the high traffic flow. When they enter our traffic simulation network, their initial time headways are smaller than the safety time headway, so they have to decelerate to maintain safety time headways with their preceding vehicles. This maneuver is not relevant with the merging vehicles from the on-ramp. However, when vehicles reach the merging point, all vehicles also suffer from rapid speed changes like scenario 1. The difference between scenario 1 and 2 is that, vehicles decelerate harder at merging point in scenario 2, since the traffic flow is higher.

In the case of the proposed protocol shown in Figure 9, similar to scenario 1, highway vehicles adjust their speeds and longitudinal positions in advance. Therefore, they can reach consensus with on-ramp vehicles and create gaps for on-ramp vehicles to merge at merging point. After all 10 vehicles finish merging maneuvers, the highway string and the on-ramp string merge to a single string on the rightmost lane of highway. From the first vehicle to the last vehicle in the string, the SIDs of them are in an ascending order.

Table 3. Simulation results of scenario 2.

	Travel Time (s)	Speed (m/s)	CO (g)	NOx (g)	CO_2 (g)	Energy (KJ)
Baseline	43.50	27.86	1.34	0.31	260.67	3624.72
Proposed Protocol	38.92	29.95	1.30	0.29	258.91	3600.31
Improved	10.50%	7.50%	2.99%	6.46%	0.67%	0.67%

As can be seen from the simulation results in Table 3, the proposed protocol improves the average travel time and the average speed by 10.50% and 7.50%, respectively, compared to the baseline. These two results lead to an improvement of traffic throughput of this simulation network. From Table 3 we can also see the proposed protocol reduces the energy consumption by 0.67%, and reduce the pollutant emission by up to 6.46%, compared to the baseline. Scenario 2 has more improvement than scenario 1 in terms of traffic throughput, energy consumption and pollutant emissions, which means the proposed protocol will bring more benefits to the traffic simulation network when the traffic flow is higher.

Conclusions and Future Work

In this study, we have proposed a distributed consensus-based cooperative methodology for highway on-ramp merging, aiming to improve system-wide traffic throughput and energy saving. The vehicle sequencing protocol has been developed for the RSU-equipped infrastructure to assign SIDs to different vehicles based on their estimated arrival time. Then the distributed consensus-based cooperative merging protocol is proposed to allow vehicles to adjust their speeds and positions in advance, and then merge in a cooperative manner. A comprehensive simulation study has been conducted based on the traffic network near UCR campus area, which shows the proposed protocol can improve the average travel time by 10.50%, the average speed by 7.50%, the energy consumption by 0.67% and the pollutant emissions by 6.46%, respectively, compared to the baseline model.

Future work of this paper may include the study of the effect on the entire highway corridor by applying the proposed protocol. Also, more factors of the traffic simulation network can be taken into consideration while proposing the methodology. For example, road grade of the analyzed area can be analyzed, since the maximum acceleration of vehicles can be heavily affected by this factor, and in turn change the maximum reachable speed of on-ramp vehicles, leading to the variety of the merging speed. CAV penetration rate also acts as a major factor, since no existing transportation system can guarantee all vehicles are connected and automated. A more realistic system which compares different CAV penetration rates can be developed in the future. Moreover, the actual vehicle dynamics model which includes powertrain model and aerodynamic drag model can also be considered as another extension of this study.

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Definitions/Abbreviations

CAV	Connected and Automated Vehicles
V2X	Vehicle-to-X
RSU	Road Side Unit
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
CV	Connected Vehicle
AV	Automated Vehicle
MOVES	MOtor Vehicle Emission Simulator
SID	Sequence IDentification
DSRC	Dedicated Short Range Communication
UCR	University of California, Riverside