

A Decentralized Cooperative Freeway Merge Assistance System using Connected Vehicles

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Abstract—With the advent of connected vehicle (CV) technology, researchers are re-engineering the design of automated highway systems using different methods such as queuing analysis and control theory to develop algorithms that can be applied to ramp metering. Earlier developments of freeway merging systems rely mainly on ramp metering and infrastructure support. These systems use centralized algorithms which require a central controller to make and communicate the control decisions. CV technology is creating new opportunities for the development of decentralized approaches to control the vehicle's operation in freeway merging systems. In a decentralized scheme, each vehicle is allowed to make their own decisions based on the information they receive from the vehicles inside the communication range and/or the infrastructure. In this paper, we present the development and implementation of a decentralized algorithm for a freeway merge assistance system using Dedicated Short Range Communication (DSRC) technology. The algorithm provides a visual advisory on a Google map through a smart phone application. To the best of our knowledge, this is one of the first implementations of a DSRC-based freeway merging assistance system -integrated with a smart phone application via Bluetooth- that has been tested in real-life on an interstate highway in an uncontrolled environment. Results from the field operational tests indicate that this system can successfully advise drivers toward a collaborative and smooth merging experience on typical “Diamond” interchanges.

Keywords—Connected Vehicle, DSRC, Merge Assistance System, Freeway, Ramps, Advisory, Decentralized System, Merge Control Algorithms.

I. INTRODUCTION

Road safety and congestion have become growing concerns over the past few years. It is estimated that in 2015 Americans in urban areas wasted about 6.9 billion hours in addition to the normal commuting time due to congestion, which translates into \$160 billion [1]. Moreover, around 1.25 million people die worldwide each year due to road crashes [2]. In addition to huge property losses, these crashes cause injuries, disabilities and even deaths. The amount of traffic-related fatalities in developed countries is alarming. For example, the total number of fatalities in the U.S. in 2014 and 2015 was 32,744 and 35,092 respectively, and the fatality percentage in the first half of 2016 was 10.4% greater than the percentage in the first half of 2015 [3]. Merging roadways are major contributors to traffic congestion and driver errors, both of which can lead to traffic accidents. Notably, merge conflicts account for about 20-30% of accidents involving heavy duty vehicles [4].

With the advent of Connected and Automated Vehicles (CAVs), the development of new and improved transportation monitoring and control systems has become possible. Attempts

have already been made to develop autonomous merging strategies to ensure safe and/or efficient cooperative vehicle merging maneuvers [5]. Most of these approaches are evaluated only through simulations where it is assumed that data from other vehicles is already available without considering the potential communication instabilities in an actual implementation. However, with the increased efforts of automotive companies to include On-Board Units (OBUs) to enable V2X communication, the implementation and evaluation of new control approaches and driver assistance systems based on the use of local information is now possible. Developers around the world are designing applications for connected vehicle (CV) environments and uploading them into the Open Source Application Development Portal (OSADP) [6] of the Federal Highway Administration in the U.S. Department of Transportation. Some examples include lane-change assistants [7], signal phase timing for emergency and transit vehicles [8], collision avoidance systems [9], signal phase and timing information [10], traffic congestion mitigation [11], crash prevention [12], etc.).

A. Related Work

Automated Highway systems have been a focus of research for more than forty years. Some of the very early efforts in this area attempted to develop automated platooning control strategies and/or merge assistance systems that relied on the use of vehicle sensor information, models [13]–[16] or more recently, infrastructure support and Internet-based vehicles [17], [18]. However, the introduction of DSRC technology and the current momentum gained by CAVs are enabling and encouraging researchers to rethink the design and implementation of automated highway systems. For example, ramp metering, i.e., the regulation of the traffic flow from the on-ramp to decrease traffic congestion on the freeway, can benefit from infrastructure information such as current traffic status to make traffic flow control decisions [19]. Lu et.al [17], [20] described a longitudinal control ramp metering algorithm using different reference points with the help of infrastructure support. Gap-responsiveness, variable speed, and coordinated ramp metering techniques have been also discussed in [20], [21].

In general, for the development of freeway merge control algorithms, several considerations have to be made. They can be designed to assist drivers in the merging maneuver or to directly control CAVs, they can be centralized or decentralized, and they can be based on heuristics or optimal control theory. A comprehensive review can be found in [5].

Some researchers have focused on providing lane-change advisory information in freeways using vehicular dynamics. For example, Park et al. [22] changed their previous fixed length safe gap lane changing advisory algorithm to allow a variable length safe gap. The variable gap is defined with respect to vehicle speed and dynamics to improve the freeway traffic and reduce merge conflicts. They collected vehicle data and provided the lane change advisory messages starting at a distance of 1500 ft before the point in which the ramp joins the main road and 1000 ft after it, where the two roads finally merge. To calculate the safety gap they considered vehicle type, vehicle length, acceleration, deceleration, and constant speed. How the drivers respond to the advisory messages is an important factor in the design of freeway merge assistance systems. Hayat et al. described driver reactions to the advisory messages in different roadway scenarios and traffic conditions. The drivers were also presented a survey questioning them about the factors they considered while responding to the advisory messages [23].

In centralized systems, there is a central controller that will make the control decisions for all the vehicles inside the communication range. In this case, the communication requirements and computational burden are very high limiting the possibility of them being implemented in real time. A decentralized system, on the other hand, allows each vehicle to make their own control decisions based on local information they receive from vehicles in the communication range, thus increasing the potential for real time implementation. Wang et al. [24] discusses a proactive and decentralized merging control algorithm that makes advisory decisions before the actual merging point. Based on the advisory decisions, vehicles on ramps and freeways can adjust their speed. However, they assumed that their algorithm knows the decision and merging points beforehand. Marinescu et al. [25], uses the concept of slot-based traffic management, where the vehicle drives inside a virtual slot. They considered V2V and V2I communication assuming that a traffic management system communicates with vehicles inside its communication range. The cooperative merging control system outperformed the baseline scenario in which all vehicles are human-driven in throughput and average delay of vehicles on the ramp. Davis [26] presents a merge control algorithm using an adaptive cruise control technique to improve the traffic throughput. In addition, researches discuss the impact of cooperative driving to merge control algorithms in [27] and [28].

Additional efforts have developed merging control approaches based on the assumption that information about the vehicle's position, speed, acceleration and time to reach the merging zone is available inside a communication range [20], [24], [29]–[34]. Rios-Torres and Malikopoulos [35], [36] addressed the problem of coordinating automated vehicles with V2V capabilities at merging roads using optimal control theory with an aim to reduce fuel consumption. A closed-form solution was derived to minimize the vehicle's acceleration while avoiding collisions with other vehicles at the merging zone. The framework was later used to analyze the energy impact of different penetration rates of CAVs on traffic and fuel consumption [37]. While this framework has provided valuable

insights on the benefits of coordinating vehicles at merging on-ramps, there is still a need for experimental implementation that can help researchers better understand and address the communication challenges that can arise in its real world deployment.

Most of the discussed approaches evaluated the performance of their algorithms using simulation tools. Few studies include the experimental evaluation of merge algorithms and those that did performed it in a controlled environment. These facts indicate that most of the algorithms found in the literature may have overlooked some of the communication challenges that might limit their actual implementation.

B. Contribution of the paper

In this paper, we utilize concepts of current state-of-the-art algorithms [18], [22]–[24] and the DSRC technology to design and implement a freeway merge assistance system that uses a three-way handshaking communication protocol to provide advisory information to drivers. We will present the design details along with the data collected in an actual field-test of the advisory system. The freeway merge assistance system will be released in the Open Source Application Development Portal after comprehensive testing.

C. Organization of the paper

The paper is organized as follows: section II describes the problem and discusses the challenges that must be addressed in order to implement the freeway merge assistance system; section III presents our technical approach to implementing the freeway merge assistance system; section IV details the work flow of the system; section V discusses the results from the field experiments; finally, we conclude in section VI stating limitations, alternatives, and future research plans.

II. PROBLEM DESCRIPTION AND CHALLENGES

Merging roadways are major contributors to traffic congestion and driver errors because there are different maneuvers that must be performed in a synchronized way in a very short period of time. In this work we address the problem of developing a driver assistance system that guides conflicting vehicles while an on-ramp driver attempts to merge onto a freeway. Based on local information received from the freeway vehicles, our proposed merging assistance system estimates the appropriate merging point and suggest actions to the conflicting vehicles. We assume the drivers follow the instructions given by the system (the problem of instruction compliance by drivers is not in the scope of this work).

Next, we will discuss the challenges to implementing the freeway merge assistance system as well as some unanticipated challenges during the collection of preliminary data in the field-testing (data collection procedure is discussed in section III-B).



Fig. 1: Circular entrance ramps in cloverleaf interchanges

1) Gap length: Accurate prediction and/or generation of safe gaps in the right lane of the freeway are crucial to providing good advisory suggestions through a freeway merge assistance application. Depending on the traffic, a merge assistance system can detect or aid the generation of safe gaps in two different ways. First, when a vehicle is traveling in the right lane, the assistance system can suggest that the vehicle changes lanes (if possible) to create a gap. This advice should be given well in advance. Second, during heavy traffic when there is no room for lane changes, the application can advise multiple vehicles traveling in the right lane to form a platoon and drive cooperatively to create a safe gap for cooperative merging. This platoon can either slow down or speed up. The estimation of the gap must be very precise and accurate.

2) Time to merge: It is necessary to calculate the time that the vehicles will reach the merging point by measuring the distance between the predicted merging point and the vehicle's current location. In our system, we use the linear distance approximation method which may not work for some entrance ramps such as the cloverleaf interchange (Fig. 1) due to their complex geometrical shape.

3) Advisory start time: The freeway merge assistance system should display the merge advisory to the drivers of all conflicting vehicles at the appropriate time. Displaying the advisory too early may cause confusion regarding the merging decision but showing the advisory information too late will leave insufficient response time for the drivers.

4) Driver response time and behavior: The effectiveness of any highway advisory application depends on the driver's response time and willingness to cooperate with the suggested advisory messages. How drivers respond to advisory messages is still an open research issue and is not in the scope of this work.

5) Vehicle lane detection: Only vehicles in the rightmost lane of a freeway will conflict with those merging from entrance ramps. Hence, the merging assistance system needs a method to identify the vehicles in the rightmost lane and to discard non-conflicting vehicles in other lanes in order to reduce the computational complexity of the system. Vehicles going the opposite direction, vehicles that have already crossed

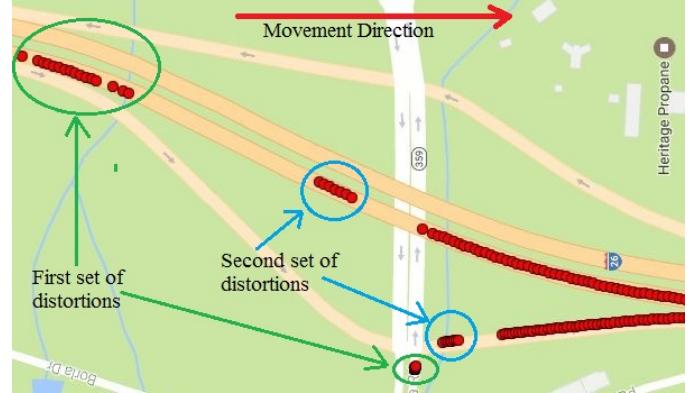


Fig. 2: Distortions in the DSRC signals

the merging point, and vehicles in opposite entrances or exit ramps are also considered non-conflicting vehicles.

6) Fog computing: DSRC enabled OBUs use most of its computational resources for disseminating safety packets. Additional computations might be burdensome for the OBUs. Therefore, it might be efficient to offload some of the complex computations to a connected smart device using the concept of fog computing. However, the communication latency between the OBUs and smart devices needs to be studied in order to find out how much computation can be offloaded without hampering the real-time execution of the system.

7) Distorted signals: DSRC signals can be distorted or lost due to structures and abnormal topography near the road such as nearby buildings, bridges, steep highways, differences of altitude, etc. We experienced distortions when collecting preliminary data as shown in Fig. 2. It might be necessary to continue extrapolating the trajectory until a further signal is received or to identify and discard the distorted data.

III. SYSTEM DEVELOPMENT

In this section, we describe the technical approaches used to develop the algorithm that implements the assistance system. The system uses the DSRC enabled OBUs to enable communication between vehicles and Android which display the advisory alerts and information to drivers. The communication between the OBUs and Android devices is established using Bluetooth connectivity.

A. Assumptions

To implement the initial version of the freeway merge assistance system, we made the following assumptions:

- 1) The system assumes that all vehicles inside the communication range of the merging scenario are equipped with a DSRC OBU.
- 2) The DSRC communication delay is negligible.
- 3) The system orders vehicles based on their time to reach the merging point. The system also determines the safe gaps in the freeway based on each vehicle's speed and time to reach the merging point.



Fig. 3: Primary location of the preliminary field-test (Interstate 26 exit 27)



Fig. 4: Secondary location of the preliminary field-test (entrance ramp to US 321)

- 4) Only the advisory system of the vehicles on the ramp observe the trajectories of the vehicles on the freeway and make the advisory decisions. The freeway vehicles only transmit basic safety messages (BSMs) and reply to the control messages using synchronization messages (more details are included in section III-C).
- 5) The freeway merge assistant system provides the advisory messages but does not guarantee the driver compliance.

B. Preliminary Data Collection

To find the appropriate time to display the advisory information, we collected BSM data while driving two vehicles on two different freeway ramps. The preliminary data collection is described below.

1) Location of the field-test experiments: We conducted field-testing on interstate I-26 (Fig. 3) and US Highway-321 (Fig. 4). We used two vehicles equipped with DSRC after-market OBUs (Arada Locomate Classic OBU [38]). One driver drove the first car on the ramp and another driver drove the second car on the freeway. Since initial timing to enter the ramp was a crucial factor to ensure the vehicles reached the merging point at similar times and collect appropriate data for analysis, we synchronized our timings by phone. This synchronized merging process was repeated a total of 8 times to obtain averaged values for the parameters of interest

2) Data storage and format: The live trajectory data collected during the preliminary field tests were stored in real-time on a USB drive as space separated values in text files. The data elements included the transmitting device ID, GPS positions



Fig. 5: Positions of the two vehicles on exit 27 of I-26 west bound (red dots represent the vehicles' position at each sample time)

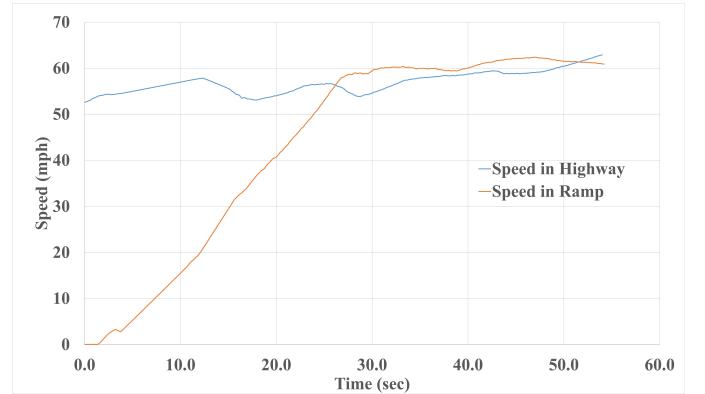


Fig. 6: Speeds of the freeway vehicle and the ramp vehicle on exit 27 of I-26 west bound

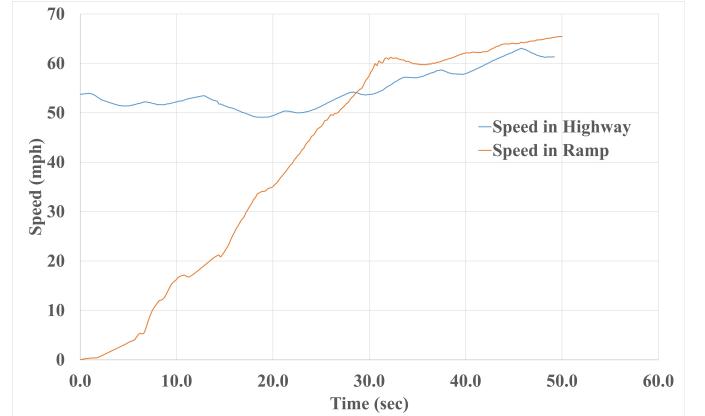


Fig. 7: Speeds of the freeway vehicle and the ramp vehicle on exit 27 of I-26 east bound

(latitude, longitude, altitude), GPS time, speed, and direction of the vehicle heading. The built-in GPS unit attached to the DSRC device calculated the speed in m/s , and it is converted to mph by our communication protocol before transmitting it.

3) Data analysis: From the preliminary data, we found that the speed of vehicles on the freeway remains almost constant. However, the speed fluctuates when a driver perceives that there are vehicles on the entrance ramp. The fluctuation

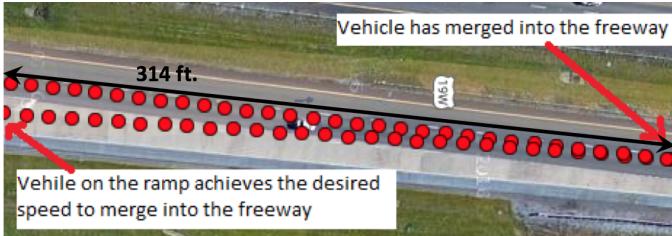


Fig. 8: Merging of the ramp vehicle into the freeway

in speed can potentially lead to merge conflicts. Fig. 6 and Fig. 7 show the speed fluctuations. From the data, we can also determine the average acceleration time, average distance covered by a vehicle on the entrance while accelerating, average merging time, and average merging distance. The average acceleration time and the time for the vehicle on the ramp to merge onto the freeway on exit 27 of I-26 west bound were 15 seconds and 3.6 seconds respectively. To calculate the merging time, we sampled the timestamps for when the vehicle on ramp achieves the desired speed to merge onto the freeway (timestamp 1483727093.8) and completely merges into the freeway (timestamp 1483727097.4), as indicated in Fig. 8. The ramp vehicle on the exit 27 of I-26 west bound covered 285 meters before achieving a speed of 60 mph and 96 meters to merge into the freeway. This data indicates that any freeway merge assistance system must start its operations at least 15-20 seconds before reaching the merging point (or 300-400 meters from the merging point).

C. Communication Protocol

The merge assistance system uses a single hop communication protocol. The step-by-step details of this protocol are described in our previous related work [39]. The system also uses a 3-way handshaking protocol (Fig. 9) to synchronize the timings of the connected vehicles. In the 3-way handshaking protocol, a vehicle can make a synchronization request to other vehicles by transmitting a control message (the format of the control message is given in Table II). Other vehicles can reply to the control message using a synchronization message

TABLE I: Format of a control message

MAC	TTC	TDM
MAC	= Address of the OBU	
TTC	= Time to reach the crash/merging point	
TDM	= Timestamp of making advisory decisions	

TABLE II: Format of a synchronization message

IER	RT	IDM	TTC
IER	= Is the vehicle on the entrance ramp?		
RT	= Amount of time spent by a vehicle on the ramp		
IDM	= Is the advisory decision made?		
TTC	= Time to reach the crash/merging point		

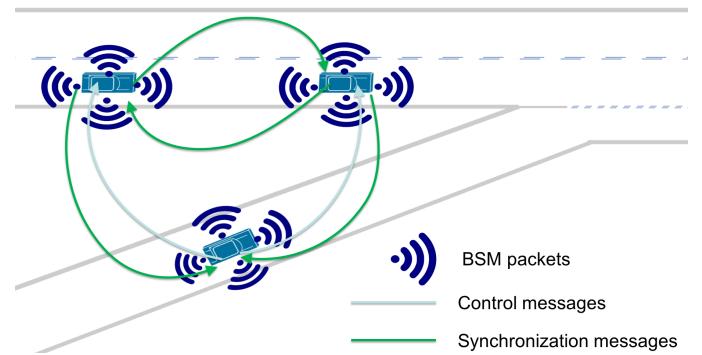


Fig. 9: 3-way handshaking protocol

TABLE III: Payload fields of a BSM packet

MAC	TS	Lat	Lon	Alt	S	Lat Dir	Lon Dir
MAC	=	Address of the OBU					
TS	=	Timestamp					
Lat	=	Latitude					
Lon	=	Longitude					
Alt	=	Altitude					
S	=	Speed					
Lat Dir	=	Latitude Direction					
Lon Dir	=	Longitude Direction					

(the format of the control message is given in Table II). The recipient of the synchronization messages can acknowledge the message by transmitting an acknowledge message. We continue to describe how and when to use the 3-way handshaking protocol in the "making advisory decisions" step described in section IV-C.

We implemented Bluetooth communication between the OBU and the Android device. Each OBU transmitted its identifier, position, speed, and direction through a transmitter program. Each OBU received and logged mobility traces of the vehicles within its range. The GPS timestamp was updated every fifth of a second so the transmitter program transmitted data five times every second.

IV. WORK-FLOW OF THE SYSTEM

The developed freeway merge assistance system executes several steps before providing advisory messages to drivers. Algorithm 1 describes the pseudo code of the core algorithm. The overall flow diagram of the system is illustrated in Fig. 10 where t_1 refers to range of time that the vehicle on the ramp spent recognizing the trajectory of the vehicles on the freeway from the information received through the BSM packets before starting the algorithm. On the other hand, t_2 refers to the range of time that the visual advisory remains active. The values of t_1 and t_2 depend of the ramp length and the calculated distance to the hypothetical merging point. Additional details are included in the following subsections.

Algorithm 1: CalculationTTC

Data: $ramps \leftarrow$ list of ramps with start positions
Result: $ttc \leftarrow$ time to reach the merging point for each vehicle

```

1 begin
2   while true do
3     packet = receiveDSRCPacket()
4     if packet == CTRL then
5       m ← unwrap(packet)
6       if m.getMAC() == MY_MAC_ADDRESS then
7         transmitSYNCMessage(ttc)
8     else if packet == SYNC then
9       m ← unwrap(packet)
10      ttc.add(m.getTTC())
11    else
12      myData ← getMyData() /* data of the vehicle that runs the algo */
13      vehicleData ← unwrap(packet)
14      NeighborTracker.track(vehicleData)/* track neighbors on the map */
15      isEnteredRamp = RampTracker.track(ramps, myData.getPosition())
16      if !isEnteredRamp then /* Only ramp vehicle observes the dynamics */
17        continue
18      if isDecisionMade then /* One time decision only */
19        continue
20      constAccel ← CalculateRampVehicleConstAcceleration()
21      if constAccel < APP_THRESHOLD_ACCEL then
22        continue
23      Map.insert(vehicleData.macaddress)
24      vehicleNo ← Map.find(vehicleData.macaddress)
25      DataQueue[vehicleNo].push(vehicleData)
26      observedTime ← getObservationTime()
27      if observedTime < APP_OBS_TIME then
28        continue
29      for each freeway vehicle do
30        sampledData ← sampleVehicleData(DataQueue, numOfSamples)
31        for each sample in sampledData do
32          mergePoint = calculateMergePoint(sample)
33          mergePoints.add(mergePoint)
34          speeds.add(sample.speed)
35          avgSpeed ← calculateAvgSpeed(speeds)
36          avgSpeeds.add(avgSpeed)
37      finalMergePoint ← calculateAvgMergePoint(mergePoints)
38      for each freeway vehicle do
39        d ← calculateDistance(sampleData.getLastSample().getPosition(), finalMergePoint)
40        t ← d/avgSpeeds.getSpeed()
41        ttc.add(t)
42      rampVehicleAvgAccel ← calculateAvgAcceleration(DataQueue)
43      d ← calculateDistance(DataQueue.getLast().getPosition(), finalMergePoint)
44      t ← solveQuadraticEqn(rampVehicleAvgAccel, DataQueue.getLast().getSpeed(), d)
45      ttc.add(t)
46      for each freeway vehicle do
47        m ← generateCTRLMessage(ttc)
48        transmitCTRLMessage(m)
49      isDecisionMade ← true

```

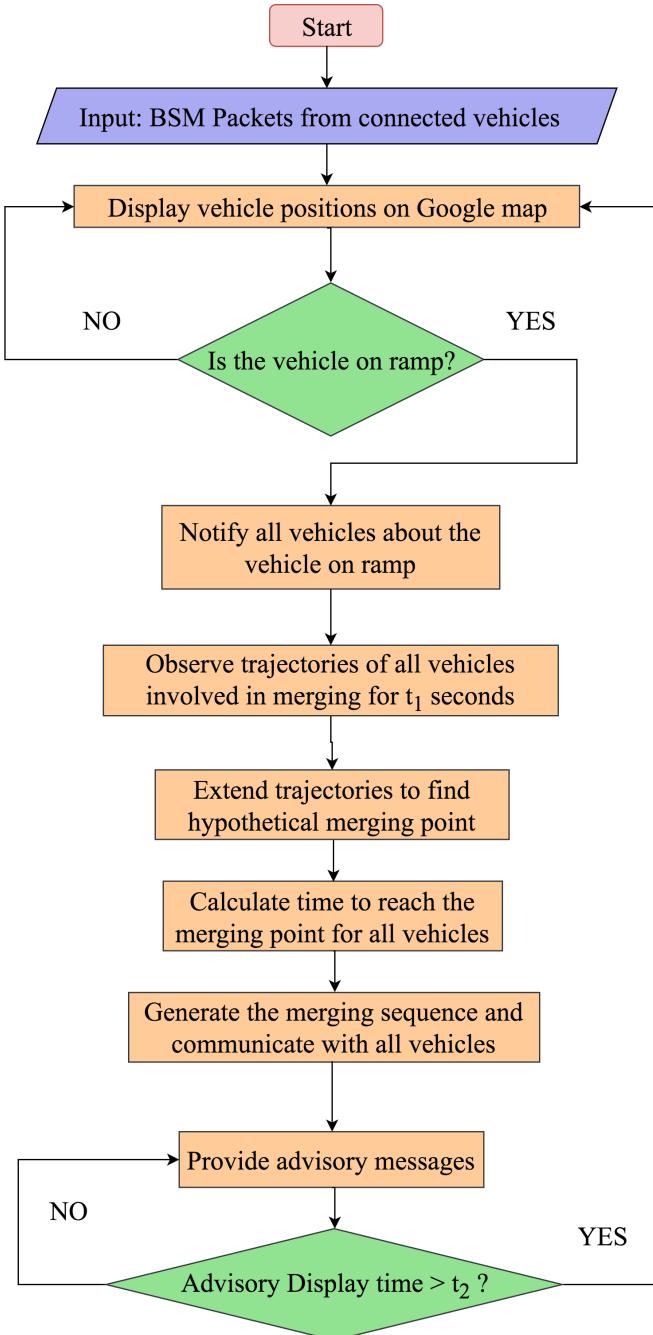


Fig. 10: Flow diagram of the freeway merging assistance system

A. Transmission and reception of BSM packets

The freeway merge assistance system transmits and receives BSM packets with the customized payload fields described in Table III. The system only receives BSM packets from vehicles within its range. The system sends data from the OBU to the connected smart phone which plots each vehicle on a map (Fig. 11 & line 14 in the algorithm). If no vehicle is within the DSRC range of the vehicle where the assistance system



Fig. 11: Three connected vehicles on the map indicated by the markers

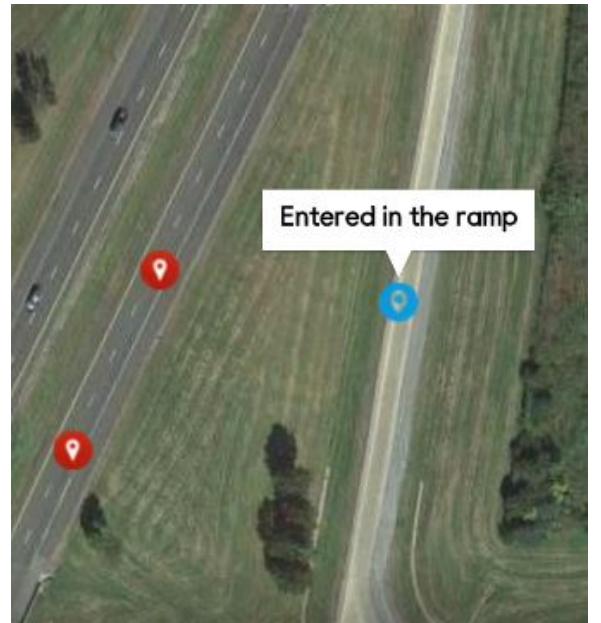


Fig. 12: A vehicle entered on the ramp

is running, then the merging assistance system plots only this vehicle on the map and provides no advisory messages. The merging system marks the current vehicle blue and all the connected/neighbor vehicles red. The system also has a ramp tracker system that repeatedly tracks if vehicles are entering the entrance ramp.

B. Observation of vehicular trajectories

If the system detects a vehicle entering an entrance ramp, it visually notifies all the drivers involved in the merging scenario about the presence of the ramp vehicle using the "**Entered the ramp**" alert message as described and depicted in Table IV and Fig. 12 respectively. This alert message alerts drivers of an oncoming merging maneuver and allows them to know the presence of vehicles on the entrance ramp before they can see them. This is especially helpful in cases where their vision is blocked by bushes or altitude differences.

TABLE IV: Advisory and alert messages of the system

Advisory and Alert Messages	Description
Entered the ramp	This alert message is sent to all the connected vehicles on the ramp and on the freeway when a vehicle enters the ramp.
Keep the speed	This advisory message is sent to the vehicle which is predicted will take the lowest time to reach and cross the merging point.
Merge behind	This advisory message is sent to the vehicle that should merge behind another vehicle.
Slow down	This advisory message is sent to the vehicle that should slow down to create a longer gap for allowing the vehicle on the ramp to merge in front.

Once the ramp vehicle achieves a constant acceleration, the merge assistance system of the ramp vehicle triggers the core algorithm and starts keeping track of the trajectories of all the vehicles, including its own, for t_1 seconds. From the observed trajectories, the system calculates t_1 merging points. The reason for calculating t_1 merging points is to reduce the error incurred by the approximation of the merging point. These errors are produced as a consequence of instantaneous speed fluctuations of freeway vehicles. The system then calculates the final merging point by averaging the t_1 merging points. Distances from the current position of the ramp vehicle to the merging point that are greater than 400m are discarded when calculating the average. The detailed mathematical approach to finding the merging point is discussed in section IV-E.

C. Generation of advisory messages

Once the system finds the final merging point, the ramp vehicle estimates the required time each vehicle will take to reach it. Then the system requests synchronization with the other vehicles by broadcasting a CTRL message to each vehicle. The CTRL message contains the timing information of the vehicle. Vehicles that receive the CTRL message reply to the message by broadcasting a SYNC message to every vehicle. The ramp vehicle then acknowledges the SYNC messages by broadcasting an ACK message to each vehicle. The ACK message contains the timing information of the ramp vehicle. Once all of the vehicles have received the ACK messages from the ramp vehicle, all the vehicles are synchronized and each vehicle has the timing information of all the other vehicles, including itself. Then the assistance system hosted by each vehicle's OBU generates the appropriate advisory message for the respective driver using the timing information. For example, if a vehicle requires the least amount of time to reach the merging point, the assistance system generates an advisory message that reads "**Keep the speed**". If the freeway vehicle requires more time to reach the merging point than the ramp vehicle, then the assistance system generates an advisory message that reads "**Slow down**". If the ramp vehicle requires more time to reach the merging point than the freeway vehicle, the assistance system generates an advisory message that reads "**Merge behind**". Notably, the determination of the safe gap to merge is not within the scope of this study and thus, the freeway merge assistance system does not make any

recommendation regarding a safe gap value when providing the "**Merge behind**" advisory message. In any case, in order to decide if a vehicle should merge between two vehicles on the freeway, the assistance system makes a reasonable estimation based on the speed and time difference of the freeway vehicles. For example, if the time required for two consecutive vehicles on the freeway to reach the merging point differs by 3 seconds and their average speed is 60mph, then the gap required for a safe merging maneuver should be around 80 meters.

D. Visualization of advisory message

Once the merge assistance system generates an advisory message, the system sends the information to the map application on an Android device using Bluetooth connectivity. The application sends the advisory message over the respective map marker as a text message and uses a bigger map marker to easily identify the vehicle being referenced by the advisory message (see Figs. 18). For example, if a freeway vehicle needs to slow down for a ramp vehicle, the application displays the "**Slow down**" message to the freeway vehicle and uses a bigger map marker to represent the ramp vehicle. Several scenarios for the advisory visualization are depicted in Fig. 18. For example, Scenario 1 illustrates a ramp vehicle being advised to merge behind the freeway lead vehicle. In this case, the "**Merge behind**" advisory message is shown over the ramp vehicle marker and a bigger map marker is used for the freeway lead vehicle.

E. Calculating the Time to Merge

To calculate the *time to merge*, we start by calculating the bearing of the trajectories for both the freeway vehicle and the ramp vehicle. Next, we find the intersection of the two extrapolated great circles (circles on the surface of the earth) using the most recent latitude-longitude coordinates and the associated bearings. This gives us the approximate merging point. We then calculate the distances to the point for both approaching vehicles. Once the distance is known, we calculate how much time is required for both vehicles to merge using the kinematic equations as described below.

1) **Find the Bearing:** The bearings for the ramp and the freeway vehicles were calculated using two subsequent GPS coordinates from the vehicle's trajectory. The bearing angles for the ramp vehicle (θ_{12}) and the freeway vehicle (θ_{34}) are illustrated in Fig. 13 and were calculated using equations (1) and (2).

$$\theta_{12} = \text{atan2}(\sin \Delta\lambda \cos \phi_2, (\cos \phi_1 \sin \phi_2 - \sin \phi_1 \cos \phi_2 \cos \Delta\lambda_{12})) \quad (1)$$

$$\theta_{34} = \text{atan2}(\sin \Delta\lambda \cos \phi_4, (\cos \phi_3 \sin \phi_4 - \sin \phi_3 \cos \phi_4 \cos \Delta\lambda_{34})) \quad (2)$$

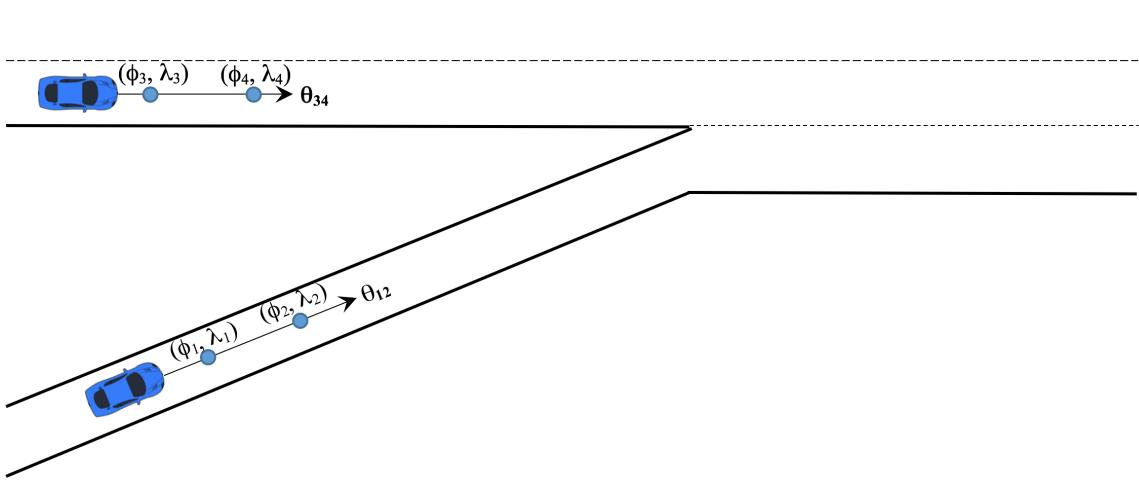


Fig. 13: Calculation of bearing angle

where,

ϕ_1, λ_1 : latitude and longitude of reference point 1
 ϕ_2, λ_2 : latitude and longitude of reference point 2
 ϕ_3, λ_3 : latitude and longitude of reference point 3
 ϕ_4, λ_4 : latitude and longitude of reference point 4

$\Delta\lambda_{12}$: the difference in longitude between points 1 and 2
 $\Delta\lambda_{34}$: the difference in longitude between points 3 and 4

2) **Find the merging point:** The key variables to calculate the hypothetical merging point are illustrated in Fig. 14. The Edward Williams' aviation formulary [40] was used for the calculation, using the following series of GIS equations:

$$\delta_{12} = 2 \arcsin\left(\sqrt{\left(\sin^2\left(\frac{\Delta\phi}{2}\right) + \cos\phi_1 \cos\phi_2 \sin^2\left(\frac{\Delta\lambda}{2}\right)\right)}\right)$$

$$\theta_a = \arccos\left(\sin\phi_2 - \frac{\sin\phi_1 \cos\delta_{12}}{\sin\delta_{12} \cos\phi_1}\right)$$

$$\theta_b = \arccos\left(\sin\phi_1 - \frac{\sin\phi_2 \cos\delta_{12}}{\sin\delta_{12} \cos\phi_2}\right)$$

if $\sin(\lambda_2 - \lambda_1) > 0$

$$\theta_{12} = \theta_a$$

$$\theta_{21} = 2\pi - \theta_b$$

else

$$\theta_{12} = 2\pi - \theta_a$$

$$\theta_{21} = \theta_b$$

$$\alpha_1 = (\theta_{13} - \theta_{12} + \pi) \% 2\pi - \pi$$

$$\alpha_2 = (\theta_{21} - \theta_{23} + \pi) \% 2\pi - \pi$$

$$\alpha_3 = \arccos(-\cos\alpha_1 \cos\alpha_2 + \sin\alpha_1 \sin\alpha_2 \cos\delta_{12})$$

$$\delta_{13} = \text{atan2}(\sin\delta_{12} \sin\alpha_1 \sin\alpha_2, \cos\alpha_2 + \cos\alpha_1 \cos\alpha_3)$$

$$\phi_3 = \arcsin(\sin\phi_1 \cos\delta_{13} + \cos\phi_1 \sin\delta_{13} \cos\theta_{13})$$

$$\Delta\lambda_{13} = \text{atan2}(\sin\theta_{13} \sin\delta_{13} \cos\phi_1, \cos\delta_{13} - \sin\phi_1 \sin\phi_3)$$

$$\lambda_3 = (\lambda_1 + \Delta\lambda_{13} + \pi) \% 2\pi - \pi$$

where,

$\phi_1, \lambda_1, \theta_{13}$: 1st starting point & bearing towards intersection

$\phi_2, \lambda_2, \theta_{23}$: 2nd starting point & bearing towards intersection

ϕ_3, λ_3 : Hypothetical merging point

δ_{12} : Angular distance between points 1 and 2

δ_{13} : Angular distance between points 1 and 3

% : (floating point) modulo

3) **Calculation of the distance:** To calculate the distance, we use the Haversine Formula [41] as shown below:

$$a = \sin^2\left(\frac{\Delta\phi}{2}\right) + \cos\phi_1 \cos\phi_2 \sin^2\left(\frac{\Delta\lambda}{2}\right)$$

$$c = 2 \text{atan2}(\sqrt{a}, \sqrt{1-a})$$

$$d = R c$$

where, ϕ is latitude, λ is longitude, R is earth's radius (mean radius = 6,371km);

4) **Use Kinematic equations to calculate the time:** Once the system finds the distances to the final merging point, it calculates the time required for each vehicle to reach the point using two kinematic equations: (i) $d = u * t + \frac{1}{2}a * t^2$ and (ii) $d = vt$. The first equation is used to calculate the time for the

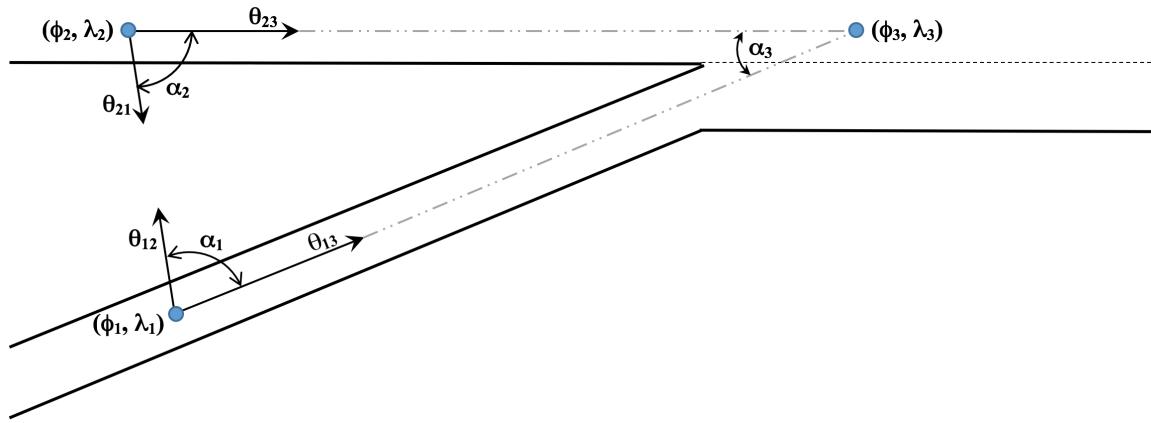


Fig. 14: Calculation of hypothetical merging point

ramp vehicle and the second equation is used for the vehicles on the freeway.



Fig. 15: Advisory displayed when the ramp vehicle merges in front of the lead freeway vehicle (Scenario 1)

V. EXPERIMENTAL RESULTS

To evaluate our model, we conducted field experiments at real freeway entrance ramps. We chose exits 27, 32, 34, and 36 for both East and West bound entrance ramps on interstate I-26. Three drivers who have valid US driver licenses and are accustomed to driving on interstates participated in the experiment. Since the experiment involved human subjects (drivers), official approval was obtained from the Institutional Review Board (IRB) of East Tennessee State University. Before conducting the experiment on the interstate, we trained the drivers on how the system works and how to interpret the advisory messages. Two drivers drove on the freeway and one drove on the ramp. The driver who drove on the ramp synchronized his timing by phone with the lead driver on the



Fig. 16: Advisory displayed when the ramp vehicle merges behind the lag freeway vehicle (Scenario 2)



Fig. 17: Advisory displayed while ramp vehicle merges behind the lead freeway vehicle (Scenario 3)

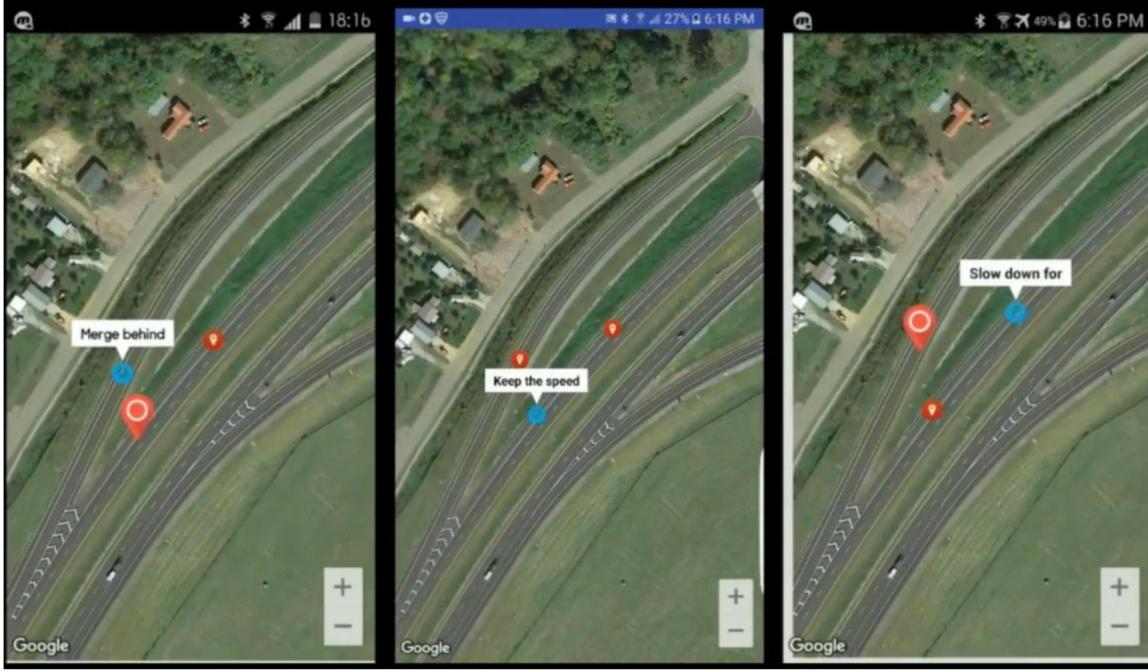


Fig. 18: Advisory visualization from three different vehicles

freeway to merge at relatively the same time so that the merge assistance system could detect a potential merge conflict. The second driver on the freeway followed the first driver, keeping a distance of around 50-100 meters. These drivers generated three scenarios as described in Table V. Figures 15, 16, and 17 show the advisory messages corresponding to the three merging scenarios displayed to the driver of the ramp vehicle through the Android device, which were captured as screen shots during the actual experiment. Figure 18 shows the advisory messages simultaneously received by all three drivers involved in the same merging scenario. Table VI describes the distance covered by a vehicle from the decision point to the merging point (Dist.), average acceleration of the ramp vehicle (Avg Accel), average speed of the freeway vehicles (Avg Speed), time to merge (TTM) values, and associated merge advisory messages of the three vehicles. In some cases, the system failed to provide advisory (shown as N/A in the table) to one of the freeway vehicles, due to incorrect approximation. The freeway system could not generate merge advisories for exit 34 (both East bound and West bound) due to an approximation error caused by a significant bend in the entrance ramps.

VI. CONCLUSIONS AND FUTURE RESEARCH

Progress in CV technology has created opportunities for researchers and automakers to develop applications that provide vehicles with new alert, warning and assistive features. This paper described a new decentralized freeway merge assistance system that uses real-world vehicular mobility traces and presented results of field-testing in an actual interstate.

TABLE V: Advisory scenarios considered for field test

Scenario 1	In this scenario, the assistance system suggests the ramp vehicle to merge in front of the freeway lead vehicle.
Scenario 2	In this scenario, the assistance system suggests the ramp vehicle to merge behind the freeway lag vehicle.
Scenario 3	In this scenario, the assistance system suggests the ramp vehicle to merge behind the freeway lead vehicle.

We evaluated the merge assistance system on eight exits along interstate I-26. Experiments demonstrate that the system can successfully provide accurate advisory information for diamond interchanges.

Driver compliance to the given advisory messages is a critical issue that significantly impacts the overall accuracy and performance of the merge assistance system. Good driver compliance is encouraged by an organized visual orientation of the advisory information because if it is not well designed it may become a source of distraction and will be difficult for a driver to follow. However, providing good visualization of advisory information while inducing a low level of distraction to the drivers is still a challenging task and further research on human factors is still required. In its current state, the merge advisory system can generate large scale data that can be used to fine-tune the system and provide initial insights on the drivers' merging behavior in response to the advisory messages.

In future work, we plan to analyze the fuel consumption and traffic implications of this proposed approach. In its current state, the merging assistance system only advises drivers to accelerate, decelerate or keep the speed and where it should

TABLE VI: Distance traveled and time required to reach the merging point from the decision point with the associated merging advisory messages

Entrance Ramp No of I-26	Ramp vehicle			Freeway vehicle 1			Freeway vehicle 2		
	Distance (m)	TTC (sec)	Avg Accel (m/s^2)	Distance (m)	TTC (sec)	Avg Speed (mph)	Distance (m)	TTC (sec)	Avg Speed (mph)
27 (WB)	136.328	3.603	3.519	132.006	2.789	47.334	107.377	2.317	46.342
	Merge behind (Freeway vehicle 1)			Advisory not generated			Keep the speed		
32 (WB)	279.746	6.958	3.543	304.243	5.741	52.994	406.324	8.140	49.915
	Merge behind (Freeway vehicle 1)			Keep the speed			Slow down for (Ramp vehicle)		
34 (WB)	-1	-1	3.688	-1	-1	44.702	-1	-1	44.966
	Merge advisory not generated (details reason in section V)			Advisory not generated			Advisory not generated		
36 (WB)	249.177	5.525	3.670	265.440	4.279	62.024	324.747	5.449	59.593
	Merge behind (Freeway vehicle 2)			Keep the speed			Advisory not generated		
36 (EB)	272.701	6.336	4.779	252.588	4.525	55.819	349.361	6.674	52.343
	Merge behind (Freeway vehicle 1)			Keep the speed			Slow down for (Ramp vehicle)		
34 (EB)	-1	-1	2.842	-1	-1	64.283	-1	-1	64.757
	Merge advisory not generated (details reason in section V)			Advisory not generated			Advisory not generated		
32 (EB)	268.663	7.179	3.080	318.373	4.968	64.081	301.152	4.386	68.647
	Merge behind (Freeway vehicle 1)			Advisory not generated			Keep the speed		
27 (EB)	166.208	5.599	2.073	168.284	2.987	56.321	193.347	3.319	58.239
	Merge behind (Freeway vehicle 2)			Keep the speed			Advisory not generated		

attempt to merge. However, we also plan to incorporate an optimal speed profile advisory to achieve a fuel and time efficient merging process.

We also plan to incorporate the merge assistance system with level one semi-autonomous vehicles. After the algorithm reaches a decision about a merging strategy, every vehicle will trigger a speed controller to ensure that they follow the given recommendations to achieve a safe and successful merging. This way we can minimize the impacts of the driver compliance issue. Finally, the algorithm will be expanded to multiple merges and enhanced through communication with roadside units. We will upload the source code to the Open Source Application Development Portal after rigorous testing.

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