Extended Driver-Assisted Merging Protocol

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***Abstract*—A safe driver assisted merge protocol was tested in a software environment to measure improvements in average vehicle throughput and average merge speed as a function of participation rate. Several enhancements to the protocol were proposed to improve the performance of the protocol in the presence of high traffic and varying ratios of ramp-to-road traffic. When the proposed projection merging assistant is used to coordinate merging vehicles, we observed an increase in maximum throughput of 80-125 vehicles/hour and a reduction in average highway delay of 80-82%.**

I. Introduction

Merging onto a highway is often a daunting task for many new drivers and even some experienced drivers. The merge maneuver, specifically in a highway on-ramp environment, requires two streams of vehicle flow of often varying velocities and throughput to combine into a single stream. This entails a series of high acceleration maneuvers by the merging vehicles and sometimes neighboring vehicles. Rapid fluctuations in vehicle velocity on a road can lead to congestion and sometimes accidents, the chances of which increase with increased traffic. These undesirable scenarios can be avoided by coordinating vehicles through the merge process.

Several advancements in vehicle technologies are under development to increase driver safety in a highway environment. Adaptive cruise control systems [1]–[4] in particular allow for vehicles to maintain a fixed velocity and safe following distance on a highway. Blind spot indicators [5] inform the driver of the presence of another vehicle in its blind spot. However, these systems do not fully assist a vehicle in performing lane change maneuvers.

The original merging assistant [6] provides assistance when a vehicle has expressed its intent to merge between two specified vehicles. Even though the protocol allows a driver to merge between these vehicles, it does not consider its impact on the other vehicles on the road. In particular, when the difference in speed is too great, this necessitated high acceleration maneuvers to accommodate the merging vehicle, which could increase highway delay and likelihood of congestion. The proposed modification takes into consideration the presence of other drivers on the road to help reduce the perturbation introduced to the highway with each merge maneuver.

A. Background

Proactive merging [7], [8] was studied as a more intelligent means of coordinating two flows of vehicles into a single flow. It was shown that planning a merge before executing it helps to increase the number of vehicles that merge. The proposed protocol adapts the velocity based proactive merging technique and combines it with the safe driver assisted merge protocol to improve the merging process on a highway on-ramp.

The improved merging assistants will be tested in a highway simulator [9] which visualizes vehicle behavior on a highway merge section based on several models. The simulator used to test the merging protocols incorporates several driver behavior models which will be used to obtain baseline measurements. The two main models, IDM and MOBIL, create the backbone of the simulator and dictate their general behavior as they travel along the simulated road.

The simulation environment for this study will be based off of an existing traffic simulator [9] written by M. Treiber. The underlying models of the traffic simulation program proposed in have already been employed by several other traffic-related works especially intelligent vehicles in the literature [4], [7], [8]. The two main models which dictate vehicle behavior are the Intelligent Driver Model (IDM) [10] and MOBIL [11] lane-changing model.

The longitudinal behavior of vehicles in the simulator is determined by the Intelligent Driver Model. The IDM is a microscopic model that approximates the behaviors of a human driver based on the desire to maintain safety spacing with the vehicle in front and to travel at a desired speed. The acceleration is a function of velocity, the actual distance to the car in front, and the safety distance which is determined by the current speed and speed difference to the car in front. The driver will decelerate if the separation distance is smaller than the safety spacing and accelerate to the desired speed when the distance in front is larger than the safety spacing. The model combines the counteracting spacing maintenance and the accelerate-to-desired-speed behaviors.

Manual vehicles perform lane changes based on the criteria specified by the MOBIL model. The lane change behavior model, MOBIL, is also based on observations of driver behavior on the highway. A driver will tend to switch to another lane in order to travel faster. Before the lane change maneuver, the driver will make sure that there will be no collision if he were change lanes. If there is a car approaching quickly in the target lane, the driver is discouraged from making the lane change. The driver changes the lane if the acceleration that he/she is allowed to travel at in the target lane is higher than the current acceleration by an amount exceeding a threshold.

II. System Overview

A. Baseline Merging Protocol

The baseline merging protocol is Driver-Assisted Merging Protocol proposed in previous work [6] as a means to safely execute lane changes through the cooperation and coordination of two adjacent vehicles in the target lane with the merging vehicle. The protocol would execute these merges in order to prevent accidents on highways while also improving merging efficiency.

The merge protocol assists a driver when the driver signals his intent to merge or change lanes by adjusting the speed of the back vehicle in the target lane to create a safe gap. The protocol will notify the driver to merge when it is safe to merge. While the speeds of participating vehicles are controlled through the adaptive cruise control systems, all lateral movements of the vehicle such as lane changes will be performed by the driver.

The baseline protocol relies on several existing and developing vehicular subsystems to coordinate the merge process. The merging protocol operates on top of the following subsystems; adaptive cruise control (ACC), coordinated sensor readings, and the reliable neighborcast protocol (RNP). In the process of merging, or to initiate the merging process, the state of the protocol on each of the participating vehicles should be synchronized by means of inter-vehicle communication. In our studies, we assume that the RNP will consistently provide reliable and guaranteed data delivery to all of the three vehicles that are participating in the merge and that all other subsystems provide sufficiently reliable service.

The protocol utilizes the existing ACC subsystems in the vehicles to safely coordinate vehicles throughout the merge process. The protocol needs to take control over the ACC system when the back car is creating a gap large enough to accommodate the merging car, and the merging car also needs the help of the ACC system to align with the gap. Since the sensor readings only provide relative information, the coordinated sensor readings system provides a consensus on sensor readings.

B. *Extended Driver-Assisted Merging Protocol*

Initial simulations using the baseline protocol showed other merges adversely affecting the merging capabilities of other vehicles on the road. An extended merging protocol was proposed to ensure that the original protocol would be used as much as possible in dense traffic. The original driver-assisted merging protocol was designed to coordinate three vehicles such that a merging car can safely enter into a space created between a front vehicle and back vehicle. However, when more vehicles are introduced into the environment, we require a means of coordinating vehicles into a state in which the original merge protocol can be executed while minimizing the chances of exiting the protocol. Furthermore, the extended protocol aims to safely merge a car while minimizing the perturbation to traffic flow, reducing the chances of congestion occurring on the main road.

To improve upon the baseline protocol, we extend the protocols control over the merging process to more intelligently choose which vehicles will be best suited for the roles of back car and front car.

C. *Construction of merge section*

In our experiment, we will consider the case where vehicles coming up on the on-ramp, travel along the acceleration lane that is parallel with the main road on the highway and merge onto the main road before reaching the end of acceleration lane. We will consider the single-lane on-ramp merges into single-lane highway to evaluate the relation between protocol participation rate and different performance metrics. The layout of the merge section is shown in Fig.1.

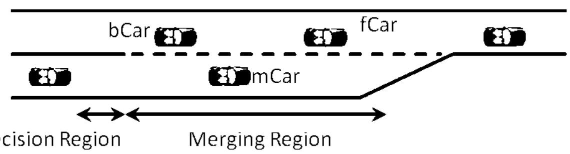

Fig. 1: Construction of merge section and the relative position of vehicles engaging in merge

D. *Assumptions*

In order to better observe the impact of the merge protocol in a highway merging environment, the following assumptions were made.

- No erratic behaviors on the highway
- The subsystems of the merge protocol work
- All the drivers on the highway have the same safety spacing requirement and desired speed
- No trucks on the highway
- Vehicle-to-Infrastructure communication systems

These assumptions were in place to focus on the influence of the different merge protocols on highway characteristics.

III. Algorithm

The projection and decision algorithm determines the best pair of cars to merge between. The chosen pair of cars is referred as back vehicle (bCar) and the front vehicle (fCar), with respect the merging vehicle (mCar). The relative position of vehicles in question is in Fig.1. The algorithm is broken down into a series of states that the merging vehicle and back vehicle transition through in order to safely guide the merging vehicle onto the main road while minimizing the perturbation introduced to the main road. The state diagrams in Fig.2 and Fig.3 summarize these state transitions.

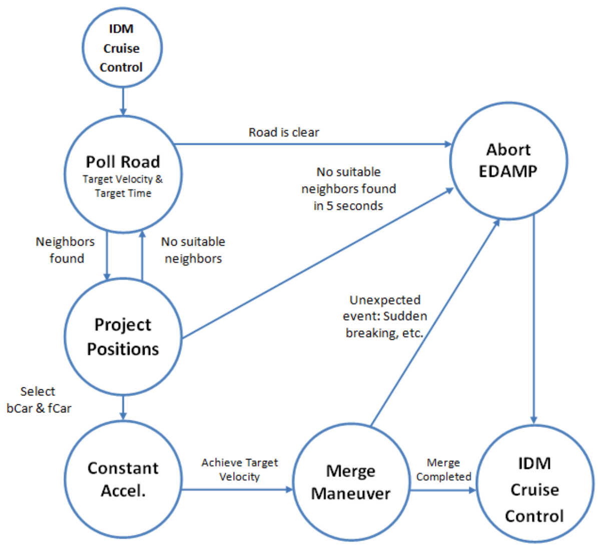

Fig. 2: State Diagram of Merging Car on Ramp

All vehicles are assumed to begin in the regular, IDM Cruise Control, state. Once the merging vehicle enters the ramp and a pre-determined decision area, it enters the polling state and polls the road to find possible back and front cars to merge between and to determine the average speed of the road. The average speed is used as mCar's target velocity

(TV). TV is used to calculate the target time (TT), the time it will take for mCar to accelerate to the target velocity.

If the road is clear, then mCar aborts the extended protocol and the driver proceeds to merge without assistance. If there are vehicles on the road, then the extended protocol uses the current speed of the main road vehicles to project where they will be in TT. A main road vehicle is selected as the back car, bCar, for mCar if it is the first car that will be behind mCar in time TT. The front Car, fCar, is selected as the car directly in front of the bCar. Both bCar and fCar must agree to participate in the merge maneuver before mCar enters constant acceleration state. If no cars satisfy the projection criteria and agree to participate in a merge maneuver then mCar repeats the polling and projection steps for up to 5 seconds, after which it aborts the extended protocol.

After mCar has reached TV and an appropriately sized space has been created between bCar and fCar, mCar enters the merge maneuver state where it begins to switch from the ramp lane to the main road. After the maneuver is complete, all the vehicles that participated in the merge return to IDM Cruise Control state.

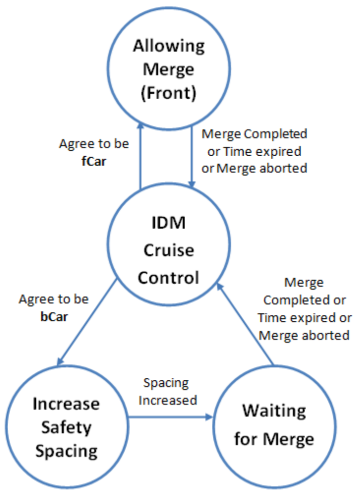

Fig. 3: State Diagram of Car of Main Road

When a vehicle agrees to be the back car, it enters the increase safety spacing state where it increases its distance from the vehicle in front of it. Once a large enough space is created, the back car enters and stays in the waiting for merge state until the merger is complete.

When a vehicle agrees to be the front car, it enters the allowing merge (front) state where its role is to warn the back and merging cars about any sudden changes ahead in the road.

IV. Simulation

To obtain an understanding of each merging protocol, we tested each protocol on a single lane highway with an on-ramp under different conditions. We measured the previously mentioned metrics under varying highway utilization, ramp-to-road traffic allocation, and percentage participation of each protocol. Since there is probabilistic factor in our simulation, to be specific, the Poisson random process of the ramp arrival, the simulation tracked vehicle dynamics over a one hour period and was repeated for 200 times with the same total input flow and ramp-to-road traffic allocation in order to obtain an average performance.

Given an expected vehicle rate on the highway and ramp based on the utilization and ramp-to-road ratio, we generate vehicles on the highway periodically, while vehicles on the on-ramp arrive according Poisson arrival processes. It is reasonable to assume that the highway vehicles arrive periodically as opposed to Poisson distribution, because if the highway is operated under moderate to high level of utilization, as in urban areas, the vehicles tend to maintain similar spacing between each other. As long as it is assumed that all drivers have the same behavior, the spacing between vehicles is the same for every vehicle under the same speed.

A. *Definitions*

There are several key dynamics of a highway merging section that will be considered for the evaluation of the merging assistant protocols. These measurements are congestion, probability of congestion, max throughput, highway delay, and ramp delay.

- Congestion: We define congestion as the condition where the average speed of traffic on first half of main road is less than 14.4km/h (8.9mph). From this we can find the probability of congestion based on the fraction of times the congestion condition is met in our simulations.
- Maximum Throughput: The maximum throughput of a configuration to be the maximum average vehicles per hour that are able to pass through the system before noticing a probability of congestion greater than 5%.
- Highway Delay: The highway delay is defined as the difference between average traveling time on the main road with and without ramp traffic. The main road delay measures the additional traveling time for a vehicle on the main road with and without ramp traffic. This is obtained by finding the average traveling time from the start of the main road until leaving the simulator of the main road vehicles when there is no vehicle coming up from the ramp, which should be the same as the traveling time of individual since all the vehicles have the same characteristics and arrive periodically. Then we subtract the traveling time without ramp traffic from the traveling time from the start of main road until the end of main road of the main road vehicles.
- Ramp Delay: Ramp delay is defined as the time between when a vehicle enters the ramp to when it exits the ramp. The average ramp delay is obtained by averaging all the ramp delay experienced by each vehicle entering the ramp.
- Highway Utilization: The highway utilization is the total number of vehicles on the highway, defined as a percentage of the maximum number of vehicles that the highway can support (1950 vehicles/hour).
- Ramp-to-Road Traffic Allocation: The ramp-to-road traffic allocation is the percentage contribution to the total highway traffic that originates from the on ramp.

These measurements will be used to evaluate the improvements achieved when vehicles merge according to the proposed protocol in a highway on-ramp environment. The results will be compared to when the vehicles merge according to the original merging protocol, and when they merge without the assistance of any protocols.

V. RESULTS

We compare the performance of the extended protocol to the baseline protocol and full manual traffic in terms of probability of congestion, the average ramp delay, and the average main road delay. For the simulation of the extended protocol and the baseline protocol, all the vehicles are assumed to participate and cooperate with each other. To evaluate and compare the performance of the extended protocol under different traffic condition, we vary the total input flow from both the main road and the ramp and the ramp-to-road traffic allocation (denoted by ramp flow ratio).

The protocol is tested under 10%, 15%, 20% and 25% of ramp-to-road traffic allocation. For each ramp-to-road traffic allocation, we test the protocol under varying input flow from 1000 vehicle per hour (vph) to 1950 vph, which is the capacity of the highway determined by the parameters of IDM model. The input flows are represented in terms of highway utilization, where an input flow of 1000 vph is a utilization of roughly 50%, and a flow of 1900 is a utilization of approximately 95%. It is not reasonable to evaluate the protocol at utilizations greater than 100% as such a scenario will always lead to congestion. Under this scenario there's no way to tell whether the congestion is due to the merging process or the overflow of highway.

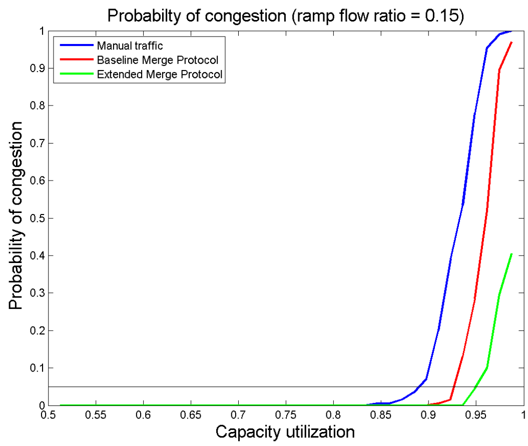

Fig. 4: Probability of congestion

Max Throughput	Manual	Baseline	Projection
10% ramp traffic	1810	1860	> 1925
15% ramp traffic	1725	1800	1850
20% ramp traffic	1710	1780	1800
25% ramp traffic	1670	1750	1750

TABLE I: Maximum throughput for different ramp traffic allocations

The performance comparison in probability of congestion under 15% of ramp traffic allocation is shown in Fig.4. The green line represents the probability of congestion of the extended protocol, while the red line and the blue line represent the probabilities of congestion of the baseline protocol and full manual traffic respectively. A horizontal line at 0.05 is drawn to mark the point where each curve exceeds 5%, where we define the maximum throughput. It is seen that at this ramp allocation, congestion is not likely to occur even as the utilization approaches 95% if all the vehicles are

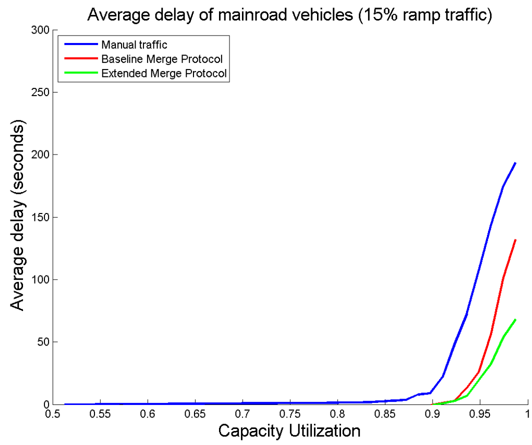

Fig. 5: Average delay of main road vehicles

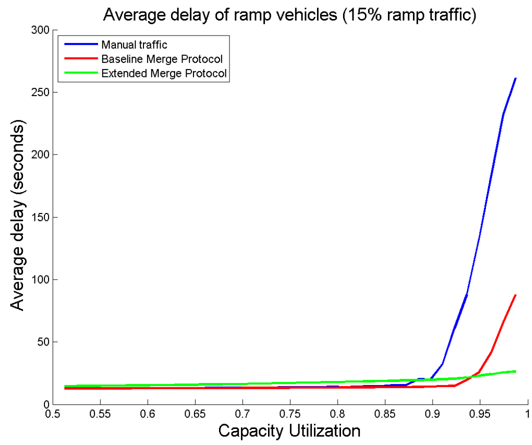

Fig. 6: Average delay of ramp vehicles

using the extended merge protocol. However, congestion is more likely to occur as the utilization exceeds 90% under manual traffic and 93% under the baseline protocol. Table I summarizes the improvement in maximum throughput of the extended protocol under other ramp traffic allocation. We can conclude that the extended merge protocol allows the highway to operate at higher utilizations without congestion.

The extended protocol achieves better performance under different ramp allocation except at 25%, under which the performance is almost the same as the baseline protocol. The reason that extended protocol has probability of congestion the same as or even higher than that of baseline protocol is that the both protocols require two vehicles on the main road to cooperate with one merge vehicle. The ratio between the flow on main road and the flow on ramp is 3:1 under 25% ramp traffic allocation. When several vehicles arrive at approximately the same time, which is characteristic of the Poisson process, some of the ramp vehicles have to wait until there are vehicles coming from upstream to cooperate with. This leads to another modification of extended protocol, which will be described in detail in the latter section. It should be noted that ramp allocations greater than 25% are unlikely in most highway systems.

To show the improvement in driving time or merging efficiency attained by using the extended merge protocol over the baseline merge protocol and manual traffic, we plot the

Highway Delay (Improvement)	Manual	Baseline	Projection
10% ramp traffic	29.8	7.8 (74%)	5.4 (82%)
15% ramp traffic	107.4	28.0 (74%)	21.4 (80%)
20% ramp traffic	162.7	77.7 (52%)	26.7 (82%)
25% ramp traffic	-	106.6 (-)	74.1 (-)

TABLE II: Average delay of main road vehicles for different ramp traffic allocations. The number in parentheses is the percentage reduction in delay with respect to manual traffic. Dash (-) indicates the delay for the manual case is too large for comparison because of congestion.

Ramp Delay (Improvement)	Manual	Baseline	Projection
10% ramp traffic	24.5	15.3 (38%)	19.6 (20%)
15% ramp traffic	132.7	25.6 (81%)	23.1 (83%)
20% ramp traffic	-	94.6 (-)	23.9 (-)
25% ramp traffic	-	162.0 (-)	33.7 (-)

TABLE III: Average delay of ramp vehicles for different ramp traffic allocations. The number in parentheses is the percentage reduction in delay with respect to manual traffic. Dash (-) indicates the delay for the manual case is too large for comparison because of congestion.

average delays for the main road vehicles and the ramp vehicles in Fig.5 and Fig.6. The results under 15% of ramp traffic allocation are shown, and the rest are summarized in Table II and Table III. Both the main road vehicle delay and the ramp vehicle delay start to increase at a higher utilization percentage compared to the baseline protocol and manual traffic. This is consistent with the measurements for probability of congestion. We expect the delay will increase under congestion since it takes more time to either merge onto the highway or drive on the highway.

At low utilization, the delay of the ramp vehicles that use extended merge protocol is 3 or 4 seconds higher than that of the ramp vehicles using baseline merge protocol. This is because when the vehicle uses extended protocol, it tends to spend more time on the ramp in order to find a suitable set of front and back cars. On the other hand, when using the baseline merge protocol, the neighboring vehicles create spacing for the merging vehicle as soon as the protocol is engaged. When the drivers merge manually, they would merge onto the highway without considering its impact on the target lane. The latter two cases are more likely to cause congestion. Moreover, it is observed during the simulation that the actual number of vehicles that complete the merge with the help of the baseline protocol is approximately only a quarter of the number of vehicles that enter the highway, as opposed to the extended protocol, in which all vehicles complete the merge by the assistance of protocol.

Overall we see improvements in all three measurements with the use of the Extended Merge Protocol.

VI. Further Improvements

Our simulations show that the extended protocol results in a higher maximum throughput and lower delays on the ramp and highway. However, these results assume that 10% of the vehicles on the road use the extended protocol. Understandably, there will be a reduction in performance when less than 100% of the vehicles use the extended protocol and therefore, additional extensions to the protocol may be needed in order for it to show significant improvements at lower participation rates.

One possible extension to the protocol is the elimination of the need for a front car to participate in the merge. We called this extension of the protocol the Reduced Driver-Assisted Merging Protocol (the reduced protocol) and it is explained in some detail later in this paper. Additional extensions that can be considered include:

- *Policing:* In this extension, if a protocol-equipped vehicle encounters a car on the ramp that is not using the protocol, the protocol-equipped vehicle will communicate with other protocol-equipped vehicles on the main road to create a merging spot on the main road for the other vehicle on the ramp.
- *Platooning:* Instead of merging one vehicle at a time, vehicles with protocol will coordinate multi-vehicle merges that form platoons on the highway. This extension will reduce delay cause by vehicles on the ramp looking for a participating vehicle on the main road.
- *Intelligent Acceleration:* In our acceleration model of the protocol, vehicles are assumed to have fixed acceleration and deceleration rates. However, allowing vehicles to vary their acceleration and deceleration rate can result in smoother merges and higher throughput.

A. *Reduced Driver-Assisted Merging Protocol*

As an extension to the extended protocol, a reduced protocol was designed to increase the opportunity to assist a driver with a merge process, even when the penetration level of the merging assistant is low.

The the extended protocol requires three vehicles with the protocol installed to be present on the highway/ramp at the same time, and that the two on the road are present one after the other. At higher penetration levels, the likelihood of this occurring for every MA Car on the ramp is high, but as the participation levels decrease, the number of manual merges increases. We modified the projection based protocol to only use the back car. This set up was tested to justify further investigation and development. We were able to achieve similar delay reductions as with the original protocol, but at a lower participation rate.

In Fig.7 we see that the reduced protocol outperforms the extended protocol and has significant improvement in ramp delay at relatively low participation rates.

When the reduced protocol and the extended protocol are compared using the probability of congestion, we see in Fig.8that at low participation rates, both protocols have similar performance, however at higher participation rates (>50%) the reduced protocol outperforms the extended protocol.

At low participation rates, we observed a small increase in the probability of congestion for both the extended protocol and the reduced protocol and an increase in ramp delay for the extended protocol. This unexpected behavior may be a result of the limits imposed on the length and number of simulations ran. Further investigation is needed into this low participation rate behavior, however, the overall results seem promising.

Even though the initial results of the Reduced Driver-Assisted Merging protocol are promising, without validating its safety the protocol is still incomplete. By evaluating the behavior of the protocol under failure events, we can demonstrate the improvements in traffic merging attainable with the

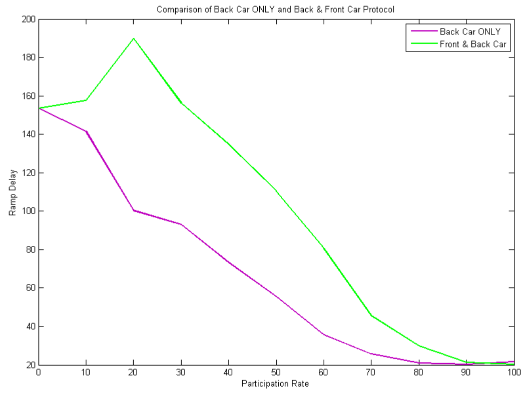

Fig. 7: Average delay of ramp vehicles for the reduced protocol and the extended protocol with varying participation rate

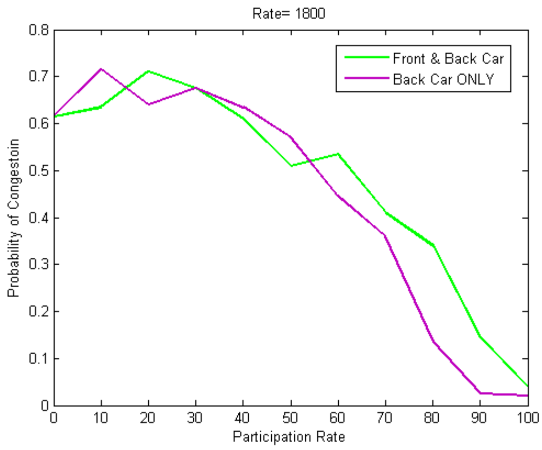

Fig. 8: Probability of congestion for the reduced protocol and the extended protocol with varying participation rate

simplified model. Improvements to increase the safety of the protocol will require extensive study of the protocol behavior under different permutations of possible failure events.

VII. Conclusion

Starting from the safe driver-assisted merging protocol, we presented an extended protocol over the baseline protocol by means of predicting cooperating vehicles and adjusting velocity of the vehicles involved before the actual merge takes place. We compared our improved protocol with the baseline protocol as well as manual traffic under different throughput and ramp-to-road traffic allocation. The simulation results showed that the extended protocol could achieve higher maximum throughput and lower delays experienced by both main road vehicles and ramp vehicles when the ramp traffic allocation does not exceed 25%.

The need to accommodate mixed traffic of manual vehicles and vehicles equipped with the protocol and to maintain better performance under high ramp traffic allocation led us to further improve the extended protocol by coordinating merge maneuver with only the back car instead of both the front car and the back car. The comparison between the three-car protocol and the two-car protocol showed that the two-car protocol starts to improve both the maximum throughput of the highway and reduce the delay at a lower penetration as compared to the three-car protocol.

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