Modelling V2V message generation rates in a highway environment

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***Abstract*—In this paper, we investigate if an analytical model can be used to estimate the load on the vehicular communication channel. We design a queueing model for estimating the probability distribution of Cooperative Awareness Message generation rates in a highway environment. The results are compared with a real world vehicular traffic trace on a highway and also with a vehicular communication simulator using Veins and SUMO for more complicated traffic scenarios involving acceleration and deceleration ramps. Comparing the results shows the probability distribution of the message generation rates predicted by our model to be within the 95% confidence interval of the distribution obtained from the traffic trace and the simulation.**

***Index Terms*—Vehicular communication, Cooperative Awareness Message, Queueing theory, Veins, SUMO.**

I. Introduction

There is currently lots of research in the field of vehicular networking. New types of V2V (Vehicle-to-Vehicle) messages are being framed to provide better travel safety, efficiency and comfort. Due to limited spectrum available for vehicular communication, with increase in message types and the penetration of V2V equipped vehicles, the load on the communication channel will also increase. This will also increase with increase in the number of vehicles within the communication range.

Another aspect that affects communication load is the maneuver performed by the vehicle. Most of the cooperative messages are event triggered. This is for instance the case for the generation of the Cooperative Awareness Message (CAM) or its equivalent in the United States, the Basic Safety Message (BSM). CAM is a basic message used in vehicular communication with a generation frequency between 1Hz and 10Hz. The message is generated based on certain conditions which depend on either the vehicle's acceleration, velocity or change in direction [1]. Similarly other type of messages will have specific conditions that need to be met. The maneuvers undertaken by the vehicles are mainly influenced by the traffic around it. For example in a typical highway, the vehicle would either accelerate, decelerate or change lanes. Hence the majority of CAMs would be generated due to vehicle acceleration or change in position. However in a roundabout, the vehicle's change in direction will also have a big influence on the message generation.

As the number of messages related to vehicular communication in a region depends on the traffic conditions and the number of vehicles, we propose to have a generic model, which when given with the traffic conditions and the Macroscopic traffic parameters [2] like traffic flow rate and average traffic speed as input, can predict the probability distribution of the message generation rates in that region. This is also what we would like to investigate in this paper: Whether an analytic model can be used to accurately estimate the message generation rate in a certain region given the traffic scenario and the general traffic parameters in that region. This will enable us to evaluate designs for different congestion control mechanisms like Decentralized Congestion Control (DCC) and channel switching mechanism for different traffic conditions. For this paper we have considered the traffic scenario in a highway environment. We show that queueing theory can be used in modelling the probabilities for different generation rates for this scenario. We evaluate our model in two different highway scenarios. Highways without acceleration/deceleration ramps and highways with acceleration and deceleration ramps. For the first scenario the accuracy of the model prediction is evaluated by comparing it with the CAM messages generated using a real world vehicular traffic trace on a multi-lane highway [3]. Since we do not posses a vehicle trajectory trace on highways with acceleration and deceleration ramps, we show that a vehicular network traffic simulation environment based on VEINS [4] can be used to model realistic traffic on highways to generate CAM messages. We use this simulation model to validate our analytical model in a more complicated scenario involving acceleration and deceleration ramps.

This paper is organized as follows. In Section II, we explain briefly the current state of the art in monitoring and dealing with the issue of communication channel load. Section III gives the design of our analytic model for predicting the CAM generation rate in a highway environment. This is followed by Section IV where our model is evaluated by comparing its results with the results obtained from vehicle trajectory traces and a vehicular communication simulator. We finally end this paper with conclusions based on our results and some future work in the direction of this research, in Section V.

II. Related Work

In this section we discuss prior work on estimating channel load. Most of these studies consider the message generation to be periodic or require actual vehicle traces to determine the message generation.

In [5], Kremer discusses the impact of road configurations and vehicle densities on the communication channel load. Their research was based on the traffic densities in different road configurations using which they were able to estimate

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the average velocity of the vehicle in that layout. However they considered the transmission range of each vehicle to be influenced by its stopping distance. Another research [6], discusses how communication density can be used as a metric for channel load in vehicular communication. Here communication density is represented as a product of vehicle density, transmission range and message generation rate for each vehicle and using simulations they showed the effect of communication density on communication performance. In both these researches message generation rate was set to a specific period. In our research we consider message generation to also be influenced by the vehicle maneuver as is the case in CAM. In [1], the authors do consider the CAM generation conditions to model the time interval between CAM generations and the size of the CAM message from the individual vehicle. However their model is based on vehicle traces and it does not examine the CAM generations over a wide area.

III. Modelling the CAM generation rate

All the vehicles participating in traffic can be categorised into different states based on the maneuver they are performing. For V2V messages which are triggered by these maneuvers, the number of vehicles in a particular state will contribute to the message generation rate, which can be used to estimate its distribution. This is demonstrated using a simple traffic scenario. In this section we formalize the traffic scenario we have considered and introduce queueing theory for modelling the CAM generation rates. We discuss the assumptions we had to consider and finally derive the probability distribution for the CAM generation rates at steady state.

A. Notation and modelling

Figure 1 shows the general traffic scenario considered for our model. It shows a section of a single direction highway connected with an acceleration ramp and a deceleration ramp. The values D_{AR} and D_{DR} denote the length of the acceleration and the deceleration ramp. The length of the main highway is denoted by D_{H}. For illustration we have further divided D_{H} to D_{H1}, D_{H2} and D_{H3}, which are the lengths of the segments H_1, H_2 and H_3 respectively. The segment H_1 consists of the vehicles entering from the previous section of the highway. The acceleration ramp merges with the highway, at the start of segment H_2 and the deceleration ramp starts at the end of H_2. H_3 consists of the vehicles that still remain on the highway and move to the next highway section. Vehicle entry into the highway is considered to follow a Poisson process [7]. Therefore on the segment H_1 vehicle i_{H} will enter the highway, $t_{i_{\text{H}}}$ seconds after vehicle $i_{\text{H}} - 1$. Similarly on the acceleration ramp vehicle i_{A} will enter $t_{i_{\text{A}}}$ seconds after vehicle $i_{\text{A}} - 1$. The values of $t_{i_{\text{H}}}$ and $t_{i_{\text{A}}}$ are independent and identically distributed, taken from exponential distributions with mean $\frac{1}{\lambda_{\text{H}}}$ and $\frac{1}{\lambda_{\text{A}}}$ respectively. From the highway, the vehicles enter the deceleration ramp with a probability p_{D} and continue on in the highway with a probability $1 - p_{\text{D}}$. As a result this traffic stream can again be modelled as a

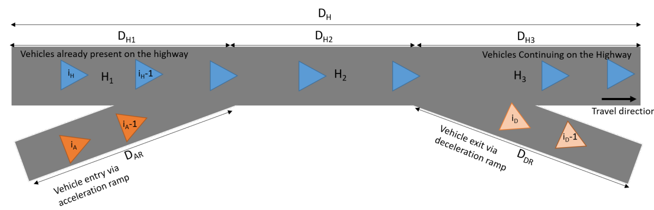

Fig. 1: Illustration of the traffic scenario being modelled

Poisson process with arrival rate onto the deceleration ramp, $\lambda_{\text{D}} = p_{\text{D}}(\lambda_{\text{A}} + \lambda_{\text{H}})$. The speed outside the highway is set to a constant v_{O}. Therefore for the vehicles entering the highway, the acceleration ramp is used by the vehicle to accelerate its velocity from v_{O} to v_i within distance D_{AR}. v_i is the cruise speed of vehicle i on the highway and is taken from a normal distribution with $\mu = v_{\text{Traffic}}$ which is the average traffic speed and standard deviation σ, since most of the studies like [8], [9] and [10] have shown that vehicle speed in free flowing traffic on highways follow a normal distribution with coefficient of variation ranging between 0.1 and 0.18. The vehicles exiting the highway decelerate from v_i to v_{O}.

Formalization of CAM generation rates

Our objective is to predict the probabilities for different CAM generation rates for this traffic scenario. We define CAM generation rate as the number of CAMs generated per second. We assume the traffic to be free flowing and the vehicles to adhere to the basic traffic rules. Therefore on the acceleration and deceleration ramps, majority of the CAMs would be generated due to change in velocity and on the highway, they would be generated mainly due to displacement of the vehicle, assuming little variation in vehicle velocity. Based on the CAM generation rules given in the ETSI (European Telecommunications Standards Institute) standard for CAM [11], we have derived the CAM generation rates for a single vehicle on the acceleration/deceleration ramps and on the main highway (segments H_1, H_2 and H_3). They are given by Eq. (1) and (2), where $g_{i,\text{a}}$ and $g_{i,\text{c}}$ are the CAM generation rate of vehicle i during acceleration/deceleration phase (on the ramps) and constant velocity phase (on the highway) respectively and v_i and a_i are its velocity and acceleration rate respectively. a_i can be represented using simple speed time equations as $a_i = \frac{|v_i^2 - v_{\text{O}}^2|}{2D_{\text{AR}}}$ for the vehicle acceleration rate on acceleration ramp and $a_i = \frac{|v_i^2 - v_{\text{O}}^2|}{2D_{\text{DR}}}$ for vehicle deceleration rate on the deceleration ramp.

$$g_{i,\text{a}} = \begin{cases} 10 & a_i > 5 \text{ m/s}^2 \\ 1 & a_i < 0.5 \text{ m/s}^2 \\ 2 \times a_i & else \end{cases} \tag{1}$$

$$g_{i,\text{c}} = \begin{cases} 10 & v_i > 40 \text{ m/s} \\ 1 & v_i < 4 \text{ m/s} \\ \frac{v_i}{4} & else \end{cases} \tag{2}$$

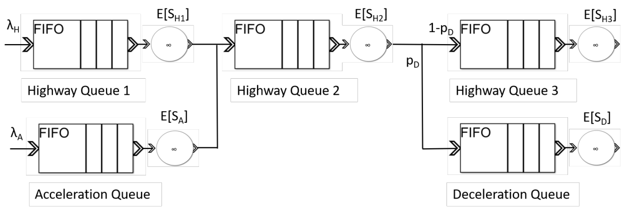

Fig. 2: Queueing network to represent the traffic scenario

Representation of the scenario using queueing theory

To obtain the steady state probability of the overall CAMs generated per unit time, we need to know the probability of the number of vehicles present in each of the segments. This is quite similar to finding the probability of the number of customers in an open queueing network [12] as shown in Figure 2. Here each of the segments in Figure 1 is represented by a M|G|∞ queue. The arrival rate of the queues will be based on the vehicle inter arrival time in each of the segments. Hence λ_{H} and λ_{A} will be the arrival rate of highway queue 1 and acceleration queue respectively. Newell in [13] shows that for a M|G|∞ queue in steady state with a homogeneous Poisson arrival rate λ, the output process will also follow a Poisson process with rate λ. Therefore the arrival rate for highway queue 2 would be $\lambda_{\text{H}}+\lambda_{\text{A}}$, for the deceleration queue would be $\lambda_{\text{D}} = p_{\text{D}}(\lambda_{\text{H}} + \lambda_{\text{A}})$ and for highway queue 3 would be $\lambda_{\text{H}} + \lambda_{\text{A}} - \lambda_{\text{D}}$. The values λ_{H}, λ_{A} and p_{D} can be used to model different highway scenarios. For example, highway without ramps ($\lambda_{\text{A}} = 0$ and $p_{\text{D}} = 0$), highway with just an acceleration ramp ($p_{\text{D}} = 0$), highway with just a deceleration ramp ($\lambda_{\text{A}} = 0$) or the start/end of a highway ($\lambda_{\text{H}} = 0$ or $p_{\text{D}} = 1$). The service times for each of the queues will be the vehicle occupancy time in the corresponding road segment. We consider a continuous movement of traffic on the highway. Therefore, all the vehicles on the highway will be serviced as soon as they enter their respective segments. Hence the number of servers for the queues is considered to be infinite. This also allows modelling the highway scenario, irrespective of the number of lanes it consists of. This is the reason for using M|G|∞ queues.

Using a queueing network to represent the traffic scenario, allows us to use the concepts related to queueing theory to determine the steady state probabilities for the number of vehicles and the CAM generation rate for this scenario. Another advantage of modelling using queues, is that we can easily extend the model to a bidirectional highway scenario by duplicating the current queueing network with the arrival rates for the vehicles arriving in the opposite direction.

B. Assumptions

1) We assume a free flowing traffic model, with average traffic speed on the highway v_{Traffic}, and initial speed of vehicles entering the acceleration ramp and the final speed of vehicles exiting the deceleration ramp to be v_{O}. In Section IV we show that this simplifying assumption has only a slight effect on our results in specific circumstances where the traffic is not free flowing.

2) Since we are considering a highway environment, we assume that 0.5 m/s$^2 < |a_i| \leq 5$ m/s^2 during the acceleration/ deceleration and 4 m/s $< v_i \leq 40$ m/s. This is inline with the vehicle velocities from the real world vehicle trace that we use to validate our model [3]. This would reduce Eq. (1) and (2) to $g_{i,\text{a}} = 2 \times a_i$ and $g_{i,\text{c}} = \frac{v_i}{4}$ respectively.

C. Steady state analysis

As mentioned in Section III-A, we use M|G|∞ queues for modelling the steady state CAM generation probability in our scenario. According to Burke's law [14], each queue in a feed-forward queueing network can be treated as if in isolation. Hence the overall steady state probability of the queueing network will be the product of the steady state probabilities of the individual queues. We first describe the calculation for the probability density function (PDF) for the CAM generation rate in the acceleration/deceleration queues and follow that up with the calculation for the highway queues (highway queue 1, highway queue 2 and highway queue 3).

1) Acceleration/Deceleration queue

For the acceleration queue, the service time of the i^{th} vehicle, $t_{i,\text{A}}$ is the time required for the vehicle to accelerate from v_{O} to v_i in distance D_{AR}. This is given by,

$$t_{i,\text{A}} = \frac{2D_{\text{AR}}}{v_{\text{O}} + v_i}. \tag{3}$$

Since v_i is taken from a normal distribution with $\mu = v_{\text{Traffic}}$ and standard deviation σ, the PDF for $t_{i,\text{A}}$, $f_{t,\text{A}}(t)$ can be calculated as,

$$f_{t,\text{A}}(t) = \frac{2D_{\text{AR}}}{\sqrt{2\pi}t^2} \times \exp\left(-\frac{\left(\frac{2D_{\text{AR}}-tv_{\text{O}}}{t} - \mu\right)^2}{2\sigma^2}\right). \tag{4}$$

From Eq. (4), the average service time $E[S_{\text{A}}]$ can approximated using Taylor series expansion similar to the procedure in [15],

$$E[S_{\text{A}}] = \frac{2D_{\text{AR}}}{v_{\text{O}} + v_{\text{Traffic}}}\left(1 + \frac{\sigma^2}{(v_{\text{O}} + v_{\text{Traffic}})^3}\right). \tag{5}$$

According to [10], σ is usually between $0.1 \times v_{\text{Traffic}}$ and $0.18 \times v_{\text{Traffic}}$ which would make $\frac{\sigma^2}{(v_{\text{O}}+v_{\text{Traffic}})^3}$ negligible. Therefore, we can reduce Eq. (5) to

$$E[S_{\text{A}}] \approx \frac{2D_{\text{AR}}}{v_{\text{O}} + v_{\text{Traffic}}}. \tag{6}$$

The steady state probability (p_k) for a M|G|∞ is the same as that for an M|M|∞ queue [13] and is given in [16]. This can be used to find the probability for having n_{A} vehicles in the acceleration queue in steady state as

$$p_{n_{\text{A}}} = \frac{(\lambda_{\text{A}} \times E[S_{\text{A}}])^{n_{\text{A}}}}{n_{\text{A}}!} \times e^{-\lambda_{\text{A}} \times E[S_{\text{A}}]}. \tag{7}$$

Substituting Eq. (6) in (7) we get

$$p_{n_{\text{A}}} \approx \frac{\left(\lambda_{\text{A}} \times \frac{2 \times D_{\text{AR}}}{v_{\text{O}}+v_{\text{Traffic}}}\right)^{n_{\text{A}}}}{n_{\text{A}}!} \times e^{-\lambda_{\text{A}} \times \frac{2 \times D_{\text{AR}}}{v_{\text{O}}+v_{\text{Traffic}}}}. \tag{8}$$

Using Eq. (1) which denotes the CAM generation rate for a single vehicle, we can express the PDF for the CAM generation rate in steady state as,

$$p_{X_\mathrm{a}} \approx \begin{cases} \frac{\left(\lambda_\mathrm{A} \times \frac{2\times D_\mathrm{AR}}{v_\mathrm{O}+v_\mathrm{Traffic}}\right)^{\frac{X_\mathrm{a}}{g_\mathrm{a}}}}{\frac{X_\mathrm{a}}{g_\mathrm{a}}\,!} \times \\ \mathrm{e}^{-\lambda_\mathrm{A}\times\frac{2\times D_\mathrm{AR}}{v_\mathrm{O}+v_\mathrm{Traffic}}} & \frac{X_\mathrm{a}}{g_\mathrm{a}} \in \mathbb{N} \\ 0 & \text{else.} \end{cases} \tag{9}$$

In the same way the steady state PDF, p_{X_d} for the deceleration queue can be calculated by substituting the corresponding arrival rate (λ_D) and the length of the deceleration ramp.

2) Highway queues

Highway segment 1 has an arrival rate λ_H and the length of the segment is defined by D_H1 The average service time $(E[S_\mathrm{H1}])$ can be calculated in the same way as in [15] when the vehicle velocity is taken from a normal distribution to give

$$\begin{aligned} E[S_\mathrm{H1}] &= \frac{D_\mathrm{H1}}{v_\mathrm{Traffic}}\left(1+\frac{\sigma^2}{v_\mathrm{Traffic}^2}\right) \\ E[S_\mathrm{H1}] &\approx \frac{D_\mathrm{H1}}{v_\mathrm{Traffic}}. \end{aligned} \tag{10}$$

The steady state probability for having n_H1 vehicles in this queue can be calculated in a similar way as in Section III-C1 to give

$$p_{n_\mathrm{H1}} \approx \frac{\left(\lambda_\mathrm{H} \times \frac{D_\mathrm{H1}}{v_\mathrm{Traffic}}\right)^{n_\mathrm{H1}}}{n_\mathrm{H1}\,!} \times e^{-\lambda_\mathrm{H}\times\frac{D_\mathrm{H1}}{v_\mathrm{Traffic}}}. \tag{11}$$

The steady state PDF for the CAM generation rate for this segment, p_{X_H1} can be derived in a similar way as p_{X_A} using Eq. (2) to give,

$$p_{X_\mathrm{H1}} \approx \begin{cases} \frac{\left(\lambda_\mathrm{H} \times \frac{D_\mathrm{H1}}{v_\mathrm{Traffic}}\right)^{\frac{X_\mathrm{H1}}{g_\mathrm{c}}}}{\frac{X_\mathrm{H1}}{g_\mathrm{c}}\,!} \times e^{-\lambda_\mathrm{H}\times\frac{D_\mathrm{H1}}{v_\mathrm{Traffic}}} & \frac{X_\mathrm{H1}}{g_\mathrm{c}} \in \mathbb{N} \\ 0 & \text{else.} \end{cases} \tag{12}$$

Similarly the PDF's for the CAM generation rate in highway queue 2 (p_{X_H2}) and highway queue 3 (p_{X_H3}) can be calculated.

3) Probability distribution of the system

The cumulative distribution function for the CAM generation rate for the entire system can be derived to a function

$$\begin{aligned} \mathrm{P(X} \leq x) = \sum_{X_\mathrm{H1}=0}^{X_\mathrm{H1}=x} p_{X_\mathrm{H1}} \times \sum_{X_\mathrm{H2}=0}^{X_\mathrm{H2}=x_1} p_{X_\mathrm{H2}} \times \sum_{X_\mathrm{H3}=0}^{X_\mathrm{H3}=x_2} p_{X_\mathrm{H3}} \times \\ \sum_{X_\mathrm{A}=0}^{X_\mathrm{A}=x_3} p_{X_\mathrm{A}} \times \sum_{X_\mathrm{D}=0}^{X_\mathrm{D}=x_4} p_{X_\mathrm{D}}. \end{aligned} \tag{13}$$

In Eq. (13), $x_1 = x - X_\mathrm{H1}$, $x_2 = x - X_\mathrm{H1} - X_\mathrm{H2}$, $x_3 = x - X_\mathrm{H1} - X_\mathrm{H2} - x_\mathrm{H3}$ and $x_4 = x - X_\mathrm{H1} - X_\mathrm{H2} - X_\mathrm{H3} - X_\mathrm{A}$.

IV. Evaluation

In order to validate the proposed model and to assess the impact of the simplifying assumptions on our results, we evaluate it in two different highway scenarios. The first scenario consist of just the highway with no acceleration and deceleration ramps. Here we compare the CAM generation rate estimated by our model with the generation rate calculated from a vehicle trajectory trace on a highway. In the second scenario, since we do not possess a vehicle trajectory trace for highways with acceleration/deceleration ramps, we evaluate our model using a vehicular communication simulator based on Veins [4] and SUMO [17]. This can be used to create realistic traffic scenarios. Finally we also evaluate the performance of our model in a non free flowing environment which can occur at high traffic loads.

A. Scenario 1: Highway without acceleration/deceleration ramps

The analytical model is compared with a vehicle trajectory trace recorded on German highways. The vehicle trace is part of the HighD project data set [3]. It provides us with the microscopic vehicle parameters which includes the vehicle speed, position and acceleration, required to calculate the CAM generation time stamps. It contains several data sets of different sections of the highway and covers 15 minutes of trace with a frame rate of 25fps, giving a time interval of 40ms. Since our model uses the macroscopic traffic parameters [2], like the traffic flow rate (λ_H), the average traffic speed (v_Traffic) and the length of the highway (D_H), we derive these parameters from the microscopic vehicle parameters [2] given in the vehicle trace. The derived values for these parameters are shown in Figure 3.

We calculated the CAM generation timestamps using the vehicle trajectory data set and the CAM generation conditions. As expected, the majority of CAMs were generated due to change in vehicle position greater than $4m$ and no CAMs were generated due to change in vehicle direction by more than $4°$. Even though there were a few CAMs generated due to change in vehicle velocity, a condition our analytical does not take into account for this scenario, its impact on the distribution of the CAM generation rate is negligible as can be seen in our results. The 95% confidence interval of the CAM generation rate from the vehicle trajectory trace is plotted using its empirical cumulative distribution based on Dvoretzky Kiefer Wolfowith inequality method [18]. Figure 3 shows the CDF of the CAM generation rate estimated by our analytical model lies within the 95% confidence interval of the CDF of the CAM generation rate from vehicle trace.

Since the vehicle trace consists of only highways without acceleration or deceleration ramps, to evaluate for complex scenarios involving ramps, we use a simulation environment. However at first we show that a simulation environment can be used to emulate real traffic behaviour by designing a traffic scenario similar to the vehicle trace in the simulation environment. Since the vehicle trace was taken on a 3 lane highway, we designed a highway environment of length 395 m with 3 lanes in SUMO. The speed limit for the highway, represented by v_H is set to 29.5 m/s which is the average speed calculated from the vehicle trace. The target speed for the vehicles is based on a random normal distribution with $\mu = v_\mathrm{H}$ and $\sigma = 0.1 \times v_\mathrm{H}$. The traffic flow rate is set to

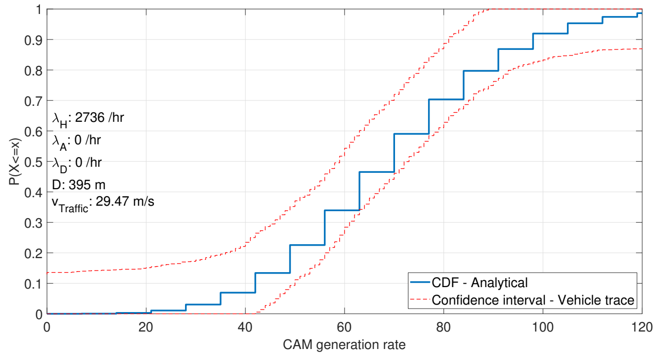

Fig. 3: Comparison of CAM generation rates between vehicle trace and the analytical model

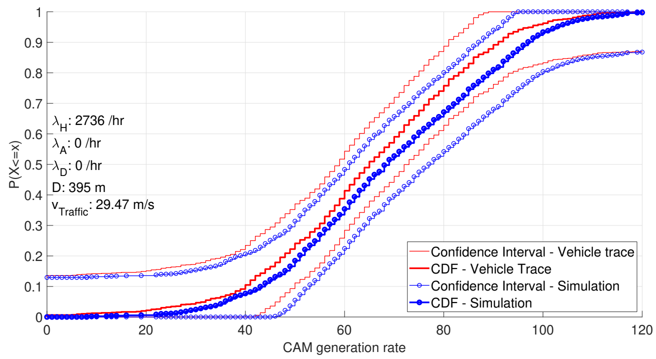

Fig. 4: Comparison of CAM generation rates between vehicle trace and the simulation model

the traffic flow rate calculated from the vehicle trace which is 2736 vehicles/hr. CAM messages were generated based on its generating conditions. Figure 4 shows the CDF of the CAM generation rates and its 95% confidence interval obtained for both the vehicle trace and the simulation model. The slight discrepancy in the CAM generation plots could be due to the fact that even though arrival rate was set to $\lambda_{\text{H}} = 0.76$, the observed arrival rate in the simulation was $\lambda_{\text{H}} = 0.73$. However, since we are able to obtain similar CAM generation distribution to real traffic trace using the simulation model, we will be using it for validating our analytical model for the scenario with acceleration and deceleration ramps.

B. Scenario 2: Highway with acceleration and deceleration ramps

A highway layout as shown in Figure 5 is designed in SUMO. The region under consideration for the CAM generation are the ones covered by D_{H1}, D_{H2}, D_{H3}, D_{AR} and D_{DR}. The vehicles inserted via the acceleration ramp have an initial velocity v_{O}, whereas the vehicles inserted on the highway have a random initial velocity such that the simulator can attain the desired traffic flow rate λ_{H}. The region covered by D_{Buf} allows the vehicles to accelerate to their cruise velocity, v_i such that, the vehicle would have reached its cruise speed by the start of D_{H1}. The speed limits, v_{H} and v_{O} are used to control the vehicle speed on the highway and outside the highway. Only the road edge after D_{DR} covered by D_{Buf} has the speed limit set to v_{O}, such that the vehicle would decelerate

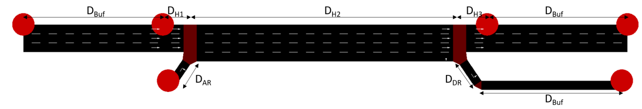

Fig. 5: Scenario 2 road layout

TABLE I: Simulation parameters

λ_{H}	0.9 (0.3 per lane)
λ_{A}	0.3
p_{D}	0.25
D_{Buf}	200 m
D_{H1}, D_{AR}	62.5 m
D_{H2}	337.5 m
D_{H3}, D_{DR}	62.5 m
Max vehicle acceleration rate	4 m/s^2
Max vehicle speed	40 m/s
v_{HLimit}	30 m/s
v_{OLimit}	20 m/s

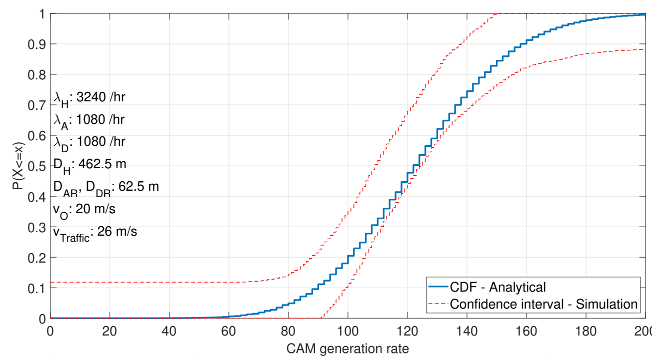

Fig. 6: Comparison of CAM generation rates between Veins simulation and the analytical model

on the deceleration ramp. The simulation parameters used for creating this scenario are given in Table I.

Since the desired vehicle speeds are based on a random normal distribution with $\mu = v_{\text{H}}$ and $\sigma = 0.1 \times v_{\text{H}}$, it is highly likely that not all vehicles will be able to reach their desired velocity due to dependency with the vehicle ahead. Therefore the average traffic speed, $v_{\text{Traffic}} < v_{\text{H}}$ This effect increases with increase in the traffic flow rate. For the current scenario, we observed that the average traffic speed on the highway to be $v_{\text{traffic}} = 26m/s$. Hence by using this in our analytical model, the CDF of the CAM generation rate estimated by our model was within the 95% confidence interval of the CAM generation rate in the simulation as shown in Figure 6.

C. Performance in non free flowing traffic

Figure 7 shows a busy highway with a high traffic flow. Since the length of D_{H2} is only 337.5m long, at high traffic flows, the vehicles do not have sufficient time to change to the appropriate lanes to either exit or continue on to the next highway section. This causes traffic jams at certain points in time closer to the deceleration ramp. As mentioned in Section III-B, we have assumed the traffic to be free flowing, such that CAMs would only be generated due to change in velocity or change in position of the vehicle. Hence our current model does not take into account the CAMs generated when the vehicle is at rest (at rest, CAMs are generated every 1 second).

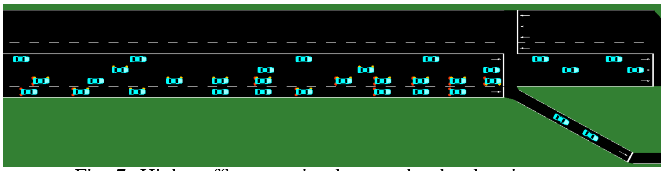

Fig. 7: High traffic scenario close to the deceleration ramp

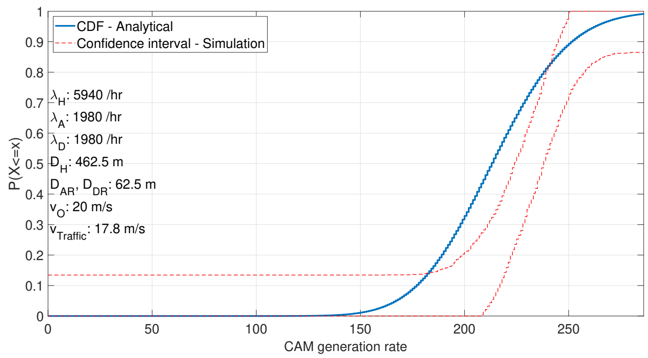

Fig. 8: Comparison of CAM generation rates between Veins simulation and the analytical model for non free flowing traffic

Due to this assumption, the analytical model underestimates the CAM generation rate for a non free flowing traffic as shown in Figure 8. Due to high traffic flow, $v_{\text{Traffic}} < v_{\text{O}}$. Hence the vehicles decelerates while entering the highway and accelerates while exiting it.

V. CONCLUSIONS AND FUTURE WORK

Through this paper we have demonstrated that analytical modelling can be used for estimating the generation rate of V2V messages using just the macroscopic traffic parameters and traffic conditions by estimating the probability of CAM generation rates in a highway environment. We have shown that our model is able to predict the CDF of the observed message generation rates with significant accuracy as shown in Section IV. Having an analytical model is useful as it would help us to narrow down the parameters that have a major effect on the channel load for a specific traffic condition. The presented model can be instrumental in analytically modelling and evaluating control algorithms for vehicular networks, such as those for decentralized congestion control and channel switching. Our model can also be used to generate (artificial) traffic in network simulators for vehicular networks. This would especially be required in the near future, as even more cooperative message types are being developed and more vehicles are being equipped with cooperative functionality, which will lead to a huge burden on the communication spectrum reserved for road safety applications.

Going forward we would like to:

1) Refine our model to more accurately capture the effect of non-free flowing traffic.
2) Modelling the message generation in other common traffic scenarios like roundabouts and intersections and extend the model to support different message types.
3) Use the model to evaluate current congestion control mechanisms such as DCC, channel switching, etc.

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