V2X Data Dissemination Delay for Vehicular Traffic Density Estimations

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***Abstract*—Distributed Floating Car Data (DFCD) corresponds to vehicles directly exchanging their floating data and cooperatively estimating the local traffic density instead of letting this task to the cloud. With a fully distributed approach, DFCD exhibits salient advantages in particular related to low latency and high reactiveness for smart mobility applications. This work proposes *DissFlow*, a DFCD solution relying on the knowledge of data dissemination delay of Vehicular-to-Everything (V2X) communications to estimate the underlying vehicular traffic density. *DissFlow* is first analytically formulated and analyzed, before being evaluated by simulation means on the iTETRIS platform. Considering a 1-D road network modeled by SUMO, simulation results show that the knowledge of the V2X dissemination delay allows to closely estimate and follow the evolutionary trend of vehicular traffic density.**

I. Introduction

The increasing vehicular traffic in urbanized areas is becoming a growing concern to local authorities. Dynamically adapting road infrastructure, such as *smart* Traffic Light Control (TLC) autonomously regulating urban intersections, are considered as potential strategies to mitigate urban traffic congestion. A critical requirement is the need for an accurate, ubiquitous, and reactive *local* traffic state estimation system.

Connected vehicles through V2X communication technologies are expected to rock the automotive world by providing revolutionary new Intelligent Transportation Systems (ITS) applications, ranging from safe and autonomous driving, smart and green mobility, or to the Internet of Vehicles (IoV). Equipped with V2X technology, vehicle become the best actors to monitor traffic states in a fully distributed and localized way. Instead of transmitting traffic states to an infrastructure system, these *smart* vehicles locally share and aggregate traffic state information through cooperative V2X communications, and then transmit traffic state estimates directly to the TLC.

TLC systems already acquire traffic states from stationary detectors despite logistic cost, detectors failures and static locations make them increasingly unadapted to monitor dynamic urban traffic. Popular for traffic state monitoring over wide areas, Traffic Information System (TIS) or Floating Car Data (FCD), such as Google Traffic, TomTom HD or Waze, cannot provide the reactivity and local traffic state precision required by TLC.

Accordingly, DFCD and Distributed Traffic Information System (DTIS) bridge both universes by providing the precision and reactivity of local traffic state estimates, with the scale of global traffic state estimates. SOTIS/SODAD, CASCADE, or Traffic View [1]–[4] represent typical examples of DFCD offering a promising alternative to stationary detectors and FCD to locally gather, share and aggregate traffic state information, without the need of external infrastructure.

One limiting factor of these DFCD approaches comes from the local traffic state sample aggregation areas. In static approaches [1], [2], [4], the challenge is to determine the zone length that is neither too large nor too small. Dynamic approaches [3], [5] adjust to true traffic conditions, but the challenge is to build and maintain dynamic clusters and cluster leaders. Also, clusters need to be mutually exclusive to avoid same samples impacting different clusters in space or in time.

In this paper, we follow a different strategy and use the physical relation between the data *dissemination delay* and the underlying *traffic density* observed for instance by [6]–[9]. Yet, we propose to revert it, and compute traffic state estimates from known dissemination delay. Accordingly, we propose *DissFlow*, a traffic state monitoring system using data *Diss*emination to extract traffic *Flow*s. We first provide an analytical formulation of the delay/density relation, and then introduce a traffic monitoring protocol controlling the dissemination process. Via simulation studies, we validate the delay/density model, and then reliability of the traffic state estimates. *DissFlow* shows to be able to closely fit to the dynamic evolution of urban traffic.

The rest of the paper is organized as follows: section II introduces the *DissFlow* protocol, while section III describes the speed/density analytical model. In section IV, we validate the analytical model and evaluate the performance of the protocol. Finally, section V covers related studies in the domain addressed in this paper, and section VI concludes the study and sheds some lights on further challenges.

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II. Protocol Description

A. Protocol Logic

From an abstract perspective, the *DissFlow* protocol operates as indicated in Fig. 1. A Road Side Unit (RSU) sends periodically a Traffic Surveillance Message (TSM), which is received by all vehicles in the area the RSU needs to monitor traffic. Only vehicles located at the entry gate (indicated in the TSM) of the area will reply with a Traffic Surveillance Data (TSD) message, which will be disseminated back in multi-hop to the RSU. Upon reception of the TSD message, the RSU extracts the delay between the initial transmission of the TSD message and its reception by the RSU, and computes the corresponding traffic density.

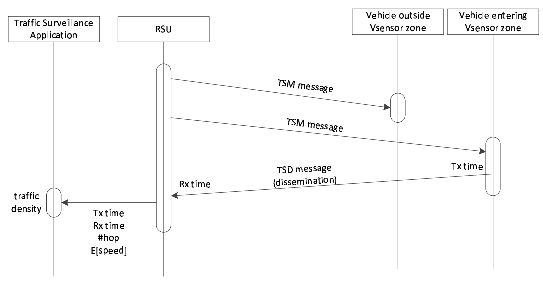


Fig. 1. DissFLow Application Logic

The traffic density is computed from the dissemination delay of the TSD messages, which alternates between forwarding and carrying phases, depending if vehicles are in a connected cluster or not. The more forwarding phases (i.e. high density), the faster will be the dissemination. Opposite, the more carrying phases (i.e. low density) the slower will be the dissemination. The TSD are purposely transmitted at a low transmit power, first to mitigate the impact on the channel, and second as the protocol favors relays and disconnections over full percolation to compute the true traffic density.

B. Dissemination Protocol

As previously described, the *DissFlow* protocol is based on two messages: TSM and TSD, corresponding to the two phases of the protocol. The first phase illustrated in Fig. 2 is to let vehicles know of the entry gates and when they should start sending a message back to the RSU. A TSM is therefore transmitted by a RSU in geo-anycast and contains location of traffic monitoring zones and their respective entry gates.

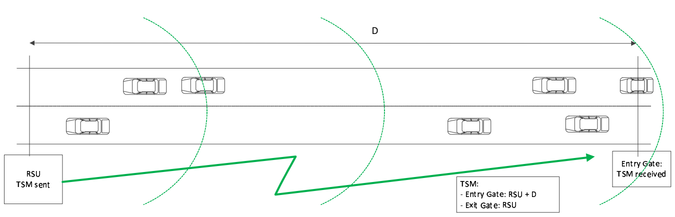


Fig. 2. Traffic Surveillance Message (TSM)

Vehicles receiving a TSM will only reply if they are at a respective entry gate of at least one of a monitoring zone indicated in the TSM. Nodes that are within these zones forward the TSM but not send any on their own, while any node outside of the zones quietly discard the TSM. TSM are also used to transmit feedback regarding the estimated traffic state estimations in order to adapt the monitoring parameters used for TSD messages.

The second phase showed in Fig. 3 corresponds to the traffic monitoring per say. Upon the reception of a TSM, a TSD message is sent back to the RSU by any vehicle crossing an entry gate in geo-unicast. The TSD message is used to record the dissemination time, the speed and local number of neighbors of each relay, as well as the hop count.

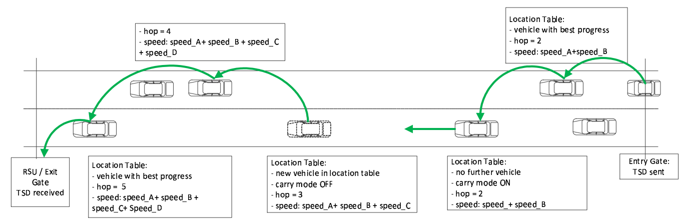


Fig. 3. Traffic Surveillance Data (TSD)

As illustrated in Fig. 3, the initiator of a TSD message forwards the message to the next best relay bringing the maximum Euclidean progress towards the RSU within the On-Board Unit (OBU) communication range. If no suitable relay is found[1], the message will be stored and carried by the vehicle. Every vehicle relaying a TSD message includes its current speed, number of neighbors and increases the hop count, so that the RSU will not only know the total dissemination delay, but also average local density and speed of these relays. Dissemination delay and average speed of relays will be used by the *DissFlow* analytical model described in Section III to compute the mean traffic volumes.

III. Delay/Density Model Description

We describe in this section the model representing the relation between the traffic density and the dissemination delay used in the *DissFlow* protocol. Parameters used in this section are described in Table I.

TABLE I
Parameter definitions

N	average number of vehicles in simulation area
L	total length of the road segment
R	Communication Range, $R << L$
N_c	average number of vehicles in connected state
L_c	length of a connected cluster
X_c	inter-distance between vehicles in a connected cluster
p_c	Probability of being in connected mode
μ	inter-distance distribution parameter
S_c	dissemination speed in connected phase
S_d	dissemination speed in disconnected phase
S_{min}	minimum vehicular speed
S_{max}	maximum vehicular speed

As depicted in Fig 4, the model is based on an hybrid dissemination process, which forwards a packet as long as a neighbor with best Euclidean progress exists, or carries it otherwise. Accordingly, a TSD message will alternate between a *Forwarding* and *Carrying* modes. Assuming the two modes

[1] Vehicles moving on the opposite direction are purposely ignored.

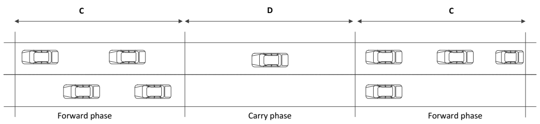


Fig. 4. Connected and Disconnected Modes

to be independant such process may be modeled as a *Renewal Process* and represented as in Fig. 5[2].

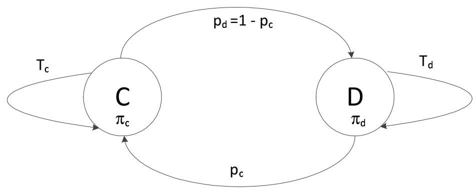


Fig. 5. Two Phases Renewal Process, where T_c and T_d represent the time spent in Connected (C), resp. Disconnected (D) state, and p_c and p_d are the probability to switch between D and C states, respectively.

Considering an exponentially distributed inter-vehicle distance, the *iid* probability of connection between two successive vehicles is given by $p_c = p(x < R) = 1 - e^{\mu \cdot R}$. Also, the number of relaying vehicles in a connected cluster may be modeled by a geometric distribution $p(N_c = N) = p_c^{N-1} \cdot (1 - p_c)$. Accordingly, the expected number of vehicles relaying a packet in a connected cluster is given by:

$$E[N_c] = \frac{1}{1 - p_c} \tag{1}$$

Also, the inter-vehicular distance in a connected cluster may be modeled by a truncated exponential distributions as:

$$E[X_c] = E[x|x < R] = \frac{\int_0^R \mu x e^{-\mu x} dx}{1 - e^{-\mu R}} = \frac{1 - e^{-\mu R}(\mu R + 1)}{\mu(1 - e^{-\mu R})} \tag{2}$$

Combining (1) and (2), the mean dissemination progress in the connected phase is given by:

$$E[L_c] = E[X_c]E[N_c - 1] \tag{3}$$

Let's define T_c and T_d as the time of a connected, resp. disconnected phase. The expected time spent by a TSD in a forwarding phase, $E[T_c]$, depends on $E[L_c]$ and the mean dissemination speed during the connected phase. Accordingly,

$$E[T_c] = \frac{E[L_c]}{S_c} \tag{4}$$

Substituting,

$$E[T_c] = \frac{1}{S_c} \frac{1 - e^{-\mu R}}{e^{-\mu R}} \frac{1 - e^{-\mu R}(\mu R + 1)}{\mu(1 - e^{-\mu R})} \tag{5}$$

The expected time spent by a TSD in a carrying phase depends on the relative speed between the currently carrying vehicle and other vehicles potentially capable of bringing the message further towards the RSU. Without loss of generality, we propose to lower bound this value by considering a maximized mutual speed. Accordingly,

$$E[T_d] \geq \frac{1}{\mu(S_{max} - S_{min})} \tag{6}$$

The hybrid (forward & carry) dissemination speed of the TSD messages is formulated as:

$$S_h = \pi_c \cdot S_c + \pi_d \cdot S_d \tag{7}$$

Without loss of generalities, S_c is approximated to light speed, although in future work, we will replace it by an analytical MAC access delay. S_d is approximated by the free flow traffic speed.

$$\pi_c = \frac{E[T_c]}{E[T_c] + E[T_d]} \tag{8}$$

$$\pi_d = \frac{E[T_d]}{E[T_c] + E[T_d]} \tag{9}$$

Substituting, the hybrid (connected & disconnected) TSM dissemination delay as a function of the vehicular density μ is given by:

$$E[T] = \frac{S_h}{L} = \frac{L \cdot (E[T_c] + E[T_d])}{E[T_c] \cdot S_c + E[T_d] \cdot S_d} \tag{10}$$

With (10), we model the relationship between the traffic density, μ, and the dissemination delay T. The traffic density estimation described in this paper however requires the opposite, i.e. the relationship between the dissemination delay and the traffic density. Without loss of generality, we propose in this work to use a reverse table lookup strategy. A set of numerical values will be sampled at a high granularity of traffic density μ, which will be stored in a database DB.

The traffic density is extracted from the dissemination delay according as follows:

$$E[\mu|T] = \begin{cases} DB(\mu|T) & \text{if entry exists} \\ DB(\lfloor\mu\rfloor|T) & \text{otherwise} \end{cases} \tag{11}$$

IV. Implementation & Results

In this section, we evaluate the reliability of *DissFlow* protocol to monitor traffic density. We implemented DissFlow on the iTETRIS ITS simulation platform [10], although we only used the ns-3 module, as we did not need to alter traffic. The iTETRIS/ns-3 is an extension of the well-known ns-3 simulator[3] with a full ETSI ITS compliant protocol stack, ranging from the ETSI ITS-G5/802.11p transceiver to the Facilities layer and Cooperative Awareness Message (CAM). The TSM and TSD messages have been disseminated according the ETSI compliant *Greedy Forwarding*[4]. We yet extended the iTETRIS/ns-3 geo-unicast implementation with a *carry* mode to handle disconnected phases in the dissemination of the TSD messages. The protocol flow of the proposed *carry* mode is illustrated in Fig. 6.

[2]If all vehicles move at the same speed, the *D* state becomes absorbing. Although included in our model, we do not describe it here due to the lack of space

[3]https://www.nsnam.org/

[4]We do not use the ETSI Store-Carry-Forward (SCF) mechanism as it would alter the dissemination delay model.

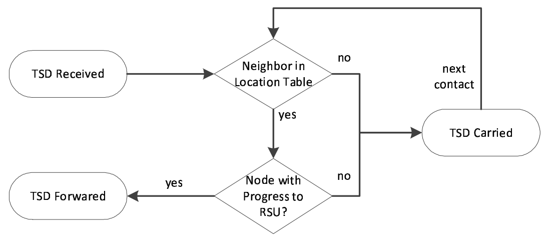


Fig. 6. DissFlow carry mode, where *progress* means *in the same direction*.

The parameters used in the evaluation are provided on Table II. We first validate the delay/density mapping model and then evaluate the traffic monitoring performance against a perfect knowledge of the true traffic density.

TABLE II
SCENARIO PARAMETERS

type	value
technology	ITS-G5/IEEE 80211.p
frequency band	10MHz @ 5.9GHz
fading	log-distance, $n = 2$
Tx power	12 dBm
TSD, TSM size	100 Bytes
scenario length	1km 1-D urban road
mean inter-arrival	$\mu = 2s$
speed (S_d)	constant, lane specific [20m/s - 40m/s]
S_c	$3 \cdot 10^8$ m/s
filter length l	100 samples
simulation time	1600s

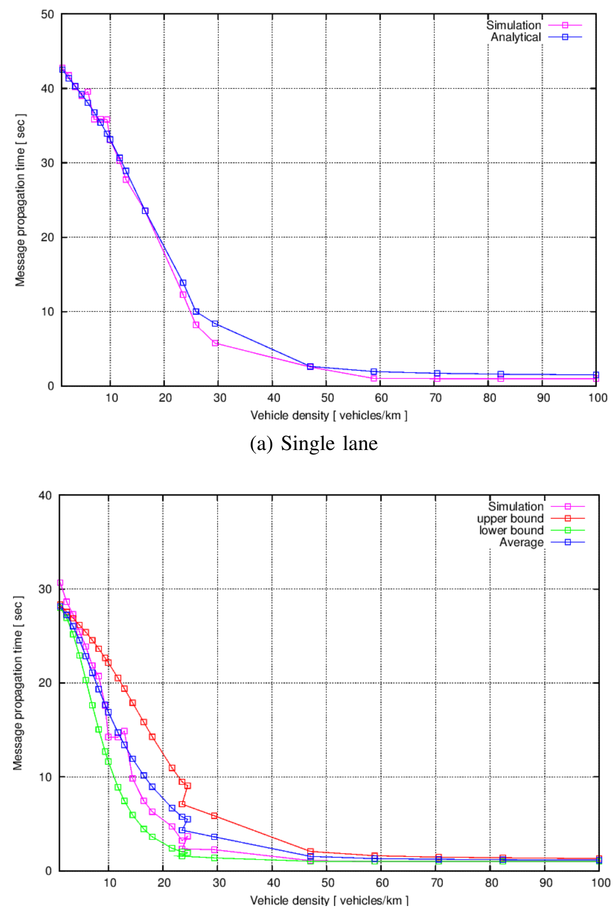
A. Model Validation

To validate the dissemination/speed model, we configured the traffic scenario with known and controllable traffic density and let vehicles passing a fixed gate to transmit a TSD message to the RSU. We extracted the dissemination time and computed the traffic density as indicated in (11). We first tested on a single lane as well as on three lanes.

Figure 7 depicts the dissemination time for the model as well as for the simulated values on iTETRIS/ns-3. As it can be observed, in both cases, the model comes very close to the simulation results, regardless if we consider a single lane or multiple lanes. As mutual speed plays a critical role in the renewal process, in particular considering multiple lanes, Fig. 7b depicts upper and lower bounds for vehicular speed, including a mean value. The influence of speed on data dissemination modeled in [9] is confirmed here.

B. Protocol Evaluation

We evaluate here the reliability of *DissFlow* to compute traffic density estimates. In order to model more realistic urban vehicular mobility, traces are extracted from SUMO [11] and injected into iTETRIS/ns-3. The vehicular arrival rate are yet still configured to follow a Poisson distribution, although its variance is significantly reduced in the high density case. We compare the traffic density estimates against the ground truth provided by SUMO.



(a) Single lane

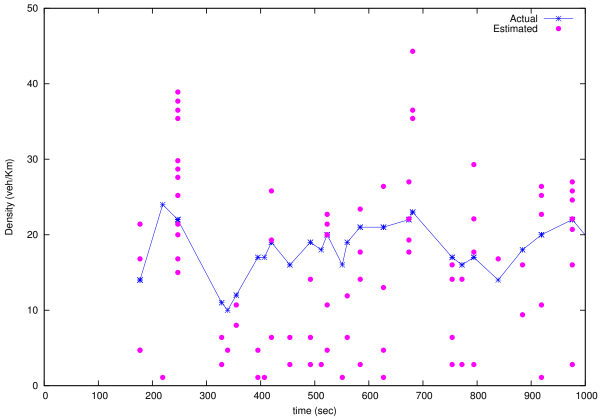
(b) Three lanes

Fig. 7. Validation of the density estimation model for 1-lan and 3-lanes traffic. The latter integrates upper and lower values for dessimination delay

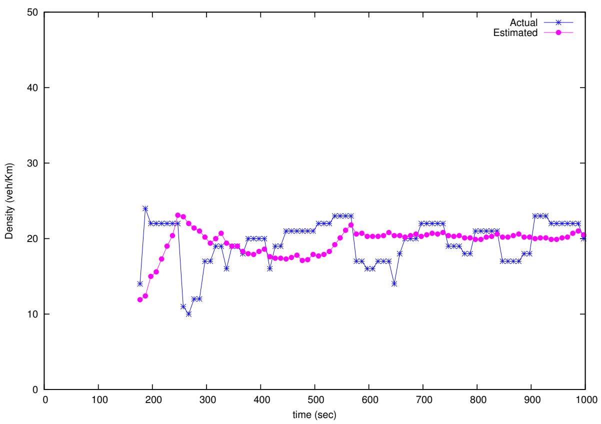
In a first step, we keep the traffic density stable (i.e. constant μ) in order to test *DissFlow* ability to reflect traffic. In a second phase, we make traffic density vary in order to evaluate the *DissFlow* capability to follow the traffic trend. In order to reduce the variability of the multiple density estimates received by the RSU, we filter the delay samples with a moving average over 100 samples.

The first set of results depicted in Fig. 8 relates to the first strategy. Fig. 8a depicts the raw samples received by the RSU, while Fig. 8a shows the filtered traffic density estimates. We can observe that *DissFlow* reproduces the traffic density, although at some occasions, it does not react to small varying states. Having a look at the raw samples in Fig. 8a, we can see that this comes from the filtering phase as well as from sparse samples.

In Fig. 9, we address the second strategy. Once again, we can observe that *DissFlow* does not react to small oscillation of traffic density. *DissFlow* is yet capable of following and matching the gradually and long term increase of the traffic density. From the raw samples, we can also observe an increasing variability of the delay samples, due to an increasing role of the relaying phase over the carrying phase. We can yet

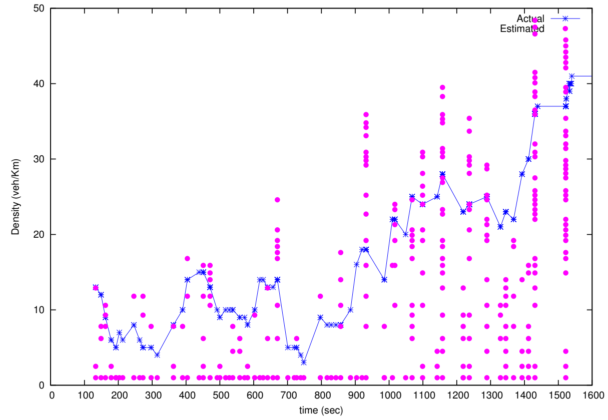


(a) Raw Received Data

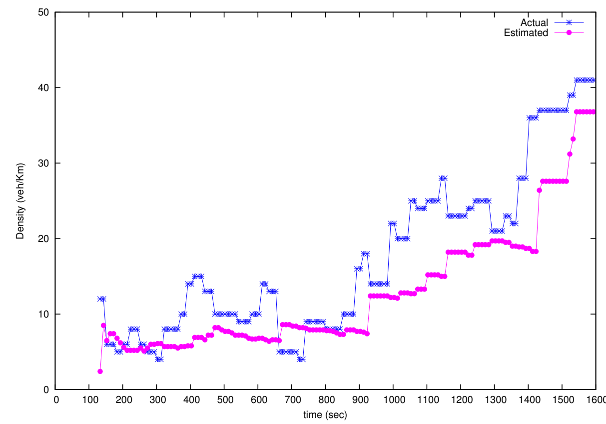


(b) Actual vs Estimated

Fig. 8. Distributed traffic density estimation, considering stable traffic density.



(a) Raw Received Data



(b) Actual vs Estimated

Fig. 9. Distributed traffic density estimation, considering dynamic and increasing traffic density.

also observe that *DissFlow* underestimates traffic density.

Overall, *DissFlow* shows to be able to fairly estimate traffic density. It does not react for brief traffic density variations, but follows the trend when the traffic shows an steady increase. It yet tends to underestimate traffic and show variability at increased traffic density. These could be explained by the hypothesis of the delay/density model, which assumes Poisson distributed inter-vehicular distances, and which are not found at high traffic density. Although the smoothing factor of *DissFlow* could be seen as beneficial to TLC systems, the filtering model will be subject to future studies to react closer to traffic density fluctuations. The overhead of *DissFlow* is measured by the number of required TSD messages, and corresponds to $\approx 30 bytes/second/vehicle$ at the highest density, which corresponds to *1/50* of the CAM overhead.

V. Related Work

A. Traffic Surveillance

Nowadays, traffic is estimated either by stationary detectors, such as inductive loops, magnetic field detectors, radar and weight in motion detectors or even cameras [12]. When traffic state information is required over large areas, FCD techniques, such as NeriCell [13], Mobile Millenium [14], *Google Traffic*, or *TomTom HD*) estimate traffic states from GPS probe data sent by vehicles over cellular networks. Compensating for low penetration of FCD vehicles, stationary detectors may also team up with FCD [15], [16].

As probing vehicles at a city-wide scale could become a burden for cellular operators, Stanica et al. [17] explored the benefits from local preprocessing of GPS probe data by elected leaders. Generalizing this approach, a larger benefit could come from not only preprocessing but fully processing traffic state locally (i.e. DFCD). One approach is to divide roads into fixed sections, in which vehicles need to consolidate traffic volumes, either directly or through a zone leader (i.e. Akhtar et. al. [18], Xu and Barth [19], SOTIS/SODAD [1], [2]). Similar approaches clustering vehicles according to similar properties rather than static road segments showed to be more adapted to dynamic traffic (e.g. Traffic View [3], CitySmart [5], or CASCADE [4]. Another approach to monitor traffic density is through Gossiping. For example, Bellavista et al. [20], MobSampling and HopSampling [21], [22] let a *sampler* broadcast a Gossip and count the returned Gossip messages to estimate traffic density. The V2X Local Dynamic Map (LDM), populated by periodic CAM / Basic Safety Message (BSM) may also be used to estimate local traffic states (e.g. Jerbi et al. [23], CoTEC [24]).

In this work, we propose to follow a different strategy and use message dissemination delays to compute the traffic state estimates. Unlike Xu and Barth [25], we yet also consider data forwarding as input to dissemination delay. Unlike [21], [22], we propose to use delay rather hop count to evaluate traffic density.

B. Data Dissemination

Several studies address the modeling of the message dissemination process in vehicular networks. Under the assumption of an exponential inter-distance [6], [7], [9], [26] characterized the relationship between the information dissemination delay and the traffic density, and prove the existence of a density threshold below which dissemination is linear, and above which dissemination becomes exponential. Wang et al. [27] relaxed the exponential inter-distance with any general distribution. Other studies further investigated this relationship and modeled the impact of a low penetration of the V2X technology on the dissemination speed [8], [9], [26].

In this work, we propose to revert this relationship and compute traffic state estimates from known dissemination delay.

VI. Conclusion and future works

We present in this paper *DissFlow*, a DFCD protocol estimating vehicular traffic density from the V2X data dissemination delay. We validated the delay/density model and evaluated its performance by mean of simulations. We notably illustrated how it can match traffic states at stable density, and steadily react to dynamic traffic density. The protocol logic also allows *DissFlow* to easily be integrated into future Probe Vehicle Data (PVD) exchanges coordinated by RSU.

In future work, we first plan to relax the Poisson inter-distance hypothesis. We then plan to investigate and find optimal values for the monitoring parameters (interval and window size). Moreover, we will also integrate MAC-layer access delay to the model, as well as use local density estimates of TSD messages to adjust the traffic state estimates at high density. Finally, we will compare *DissFlow* with other DFCD approaches.

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