A comprehensive simulation environment for testing the applications of a V2X infrastructure

Apratim Choudhury[1], Tomasz Maszczyk[2], Chetan B. Math[3], Hong Li[4] and Justin Dauwels[5]

***Abstract*—It is a well established fact that road transportation is one of the major contributors of greenhouse gases. The increase in the number of light and heavy vehicles in cities everyday is providing additional impetus to this predicament. A solution for reducing greenhouse gas emissions would be to "engineer" traffic to decrease congestion. One particular engineering-based solution can be to provide a Green Light Optimized Speed Advisory (GLOSA). This method involves communicating the remaining phase time to vehicles approaching a junction, which can be used to compute an approach speed that will not require the vehicle to stop. However, the field implementation of this solution would require installation of communication devices on both traffic signal heads and on vehicles, which would involve considerable cost and policy changes. Therefore, before implementation, it is desirable that any predicted benefits be gauged using alternative means, so that the profitability of the installed infrastructure can be justified. We therefore present, a novel simulation platform, which combines VISSIM, MATLAB and NS3 in order to model the various components of a V2X-based application such as GLOSA with a high level of fidelity. In this chapter, we apply this simulation platform to compute the benefits of implementing GLOSA on two intersections, one located in Singapore and the other located in Eindhoven, in the Netherlands. The results illustrate the reduction in fuel consumption and queue length due to the execution of GLOSA, for different traffic flows, communication parameters, levels of V2X penetration and traffic signal policy.**

***Index Terms*—GLOSA, Green Wave, V2X Simulation**

I. Introduction

It is being predicted that the issues pertaining to traffic management and efficiency can be greatly mitigated with the presence of a V2X communication infrastructure. A V2X communication network is a vehicular ad-hoc network that enables vehicles to communicate with each other and with road-side infrastructure units that are within a certain neighbourhood of each other. This network allows access to real-time traffic information that can be leveraged to allow implementation of sophisticated traffic control and vehicle routing algorithms. However, setting up an infrastructure of such a magnitude would involve a sizeable fiscal investment and substantial policy changes. Therefore, before any traffic management strategy built upon a V2X foundation can be implemented on a wide scale, a phase of thorough testing and verification to ensure that the implementation can indeed bring about benefits in traffic movement, is highly warranted. Conducting field tests will be expensive and unrealistic in early stages and the only time and cost feasible way of obtaining the relevant data is by carrying out exhaustive simulations. The simulations will need to re-create traffic scenarios as accurately as possible in addition to modelling the communication network with a high level of fidelity so that results derived can be deemed realistic. In order to address this need, the authors have developed a simulation platform that combines three software packages, VISSIM (traffic modelling),MATLAB (traffic management applications) and NS3 (communication network simulation).

In metropolitan cities, traffic congestion is emerging as one of the major challenges that need to be overcome [1]. Everyday, a growing number of vehicles are being added to the existing fleet, putting more stress on the already overburdened transportation infrastructure. Traffic congestion not only results in a lot of wasted hours for commuters, but also affects their health and well-being [2]. In addition, according to Barth et al. [3], driving patterns typical of a congestion involving frequent acceleration and deceleration in succession, lead to higher CO2 emissions than if traffic were moving at steady state speeds, even if the average speed is equal for both cases. In order to address these issues, policy-makers are concentrating more on approaching the problem at a microscopic level. Their approach is to push car-manufacturers to incorporate improvements in the vehicles. Such improvements include efforts to make vehicles lighter, improve the power-train, and use alternative fuels. However, these technologies have still a long way to go before full implementation and market penetration. In order to bring about an effective reduction in emissions, it is important that the root cause be attacked, which is the intensification of congestion in major cities.

There are already some intelligent traffic management systems existing around the world. In Singapore, the Green Link Determining System (GLIDE) [4], [7] is in operation. This system is an adaptation of the Sydney coordinated adaptive traffic system (SCATS) system [5] that applies real-time traffic information to establish the signal scheduling policy. In addition, there are the TrafficScan [6], Junction Electronic Eyes (J-EYES) and the Expressway Monitoring Advisory System (EMAS) [7]. However, most global traffic management solutions are reactionary systems that are

*This work is supported by the NTU-NXP Intelligent Transport System Test-Bed Living Lab Fund S15-1105-RF-LLF from the Economic Development Board, Singapore

[1]Apratim Choudhury is with Siemens Mobility, Singapore apratim.choudhury@siemens.com

[2]Tomasz Maszczyk is with the Institute of High Performance Computing, A-STAR, Singapore maszczyk_tomasz_karol@ihpc.a-star.edu.sg

[5]Justin Dauwels is with Faculty of Electrical and Electronics Engineering Nanyang Technological University, Singapore jdauwels@ntu.edu.sg

[3]Chetan B. Math is with the Institute of Infocomm Research, A-STAR, Singapore Chetan_B_M@i2r.a-star.edu.sg

[4]Hong Li is with NXP Semiconductors Eindhoven, Netherlands hong.r.li@nxp.com

activated only when a congestion is observed on any part of the traffic network. A more proactive system to tackle congestion will be to implement a strategy that brings about a uniformity in the traffic movement profile, such as the Green Light Optimized Speed Advisory (GLOSA) [8]. Therefore, the aim of the this work is to utilize the integrated simulation environment [9] consisting of VISSIM (traffic simulation), NS3 (communication simulation) and MATLAB (V2X application modelling) to analyse as exhaustively as possible, whether application of GLOSA leads to any benefits with regards to fuel consumption and queue length. GLOSA simulations are carried out with both a fixed-time traffic signal policy and also the GLIDE system in order to compare the differences in the effects, that GLOSA may have. Our aim with this chapter is to demonstrate the capability of the simulation platform to model and assess various facets of a large-scale V2X application. To illustrate the versatility, we obtain results by adding variation to the following traffic and communication parameters:

1) Traffic Parameters
   a) Traffic Network
   b) Vehicle Volume
   c) Traffic Signal Timing policy
   d) V2X penetration rate
2) Communication Parameters
   a) Transmitter Power
   b) Receiver Energy Detection Threshold
   c) Data Rate.

Also, as far as we know, GLOSA for GLIDE has not yet been implemented in a testbed or simulation platform, moreover, the benefits of GLOSA have not yet been assessed on a realistic traffic network.

A precursor to the widespread implementation of GLOSA is the existence of a V2X (Vehicle-to-Vehicle/Vehicle-to-Infrastructure) communication foundation [10]. Over the past decade, the area of vehicular communication has received much attention, mainly to improve safety [11] and efficiency on roads [12]. V2X communication typically utilizes the IEEE 802.11p protocol because it allows communication outside the context of the Basic Service set. This leads to lower latency in the communication, making V2X highly suitable for safety-critical applications. GLOSA will leverage on V2X communication technology to advise drivers of the optimal speed that they need to drive on. However, installation of V2X communication units across entire road networks of a city and on board vehicles will involve heavy costs and policy changes. Hence any predicted benefits of installing them will need to have convincing quantitative justification. In this regard, the tool can potentially be utilized to test optimal placement configuration of Road Side Units (RSU) and levels of penetration for vehicle On-Board Units (OBU).

The chapter is organized as follows. In section II-A, a review of existing V2X simulation platforms and their shortcomings has been presented. In sections II-B and II-C, we discuss congestion mitigation using traditional ITS, and V2X based techniques, while in section II-D we review of the research work carried out towards conception and testing of GLOSA. In section III, we describe design of the simulation environment with the parametric setup detailed in section IV. We present our results in section V. We offer concluding remarks and ideas for future research in section VI.

TABLE I: V2X simulation platforms

Simulation Platform	Advantage	Disadvantage
VsimRTI [13]	Ability to integrate multiple traffic and communication simulators. For ex: SUMO (Traffic), JiST/SWANS (communication), MATLAB CCMSim (Communication) and OMNET++ (Communication)	No interface for VISSIM
Multiple simulator Interlinking for IVC [14]	Integrates VISSIM, MATLAB and NS2	Not upgraded for NS3
iTetris [15]	Integrates SUMO and NS3 using an iTetris control system middle-ware that promotes extendibility of the architecture	No provision to integrate VISSIM
Veins [16]	Integrates SUMO with OMNET++	No provision to integrate VISSIM
NCTUns 6.0 [17]	Highly integrated traffic and network simulator	Limited flexibility to integrate 3rd party simulators
TraffSim [27]	Highly detailed traffic simulation and fuel consumption model	No extensions for communication simulation

II. Related Work

A. V2X simulation platforms

In Table I, we provide an overview of some of the major simulation environments for testing V2X protocols and applications, along with the shortcomings that motivated us to develop our own simulation environment. An important requirement that any given simulation tool needed to fulfil, was the usage of VISSIM for traffic simulations. Our decision to implement the intersection models in VISSIM can be attributed to the following reasons: (1) it is able to accurately replicate the trajectories of different classes of vehicles in simulation; (2) allows a simulation resolution of 50 ms, which would enable testing V2X applications that require split second responses from the vehicle; (3) has inbuilt models for fuel consumption and queue length calculation and (4) provides real-time data exchange with external programs and allows modification of vehicle behaviour based on stimuli provided through same programs.

For a more detailed review, we refer the reader to [9].

B. Existing traffic congestion mitigation methods

Different cities have adopted a number of techniques for traffic congestion management. As two illustrations, we will consider here briefly Singapore and the Netherlands. In Singapore, Intelligent Transportation Systems (ITS) based solutions such as GLIDE [4], [7], TrafficScan [6], J-Eyes, EMAS [7] and ERP [18] are already in place.

TABLE II: Existing congestion mitigation strategies in Singapore and Eindhoven

	Strategy	Principle	Disadvantage
Singapore	Electronic Road Pricing	Congestion pricing	Reactive system coming into effect only when a congestion incident occurs
	GLIDE	Traffic smoothing using signal control	
	Traffic Scan Junction Eyes EMAS	Incident management	
Eindhoven	*Groene Golf*	Traffic smoothing using signal timing coordination	
	UTOPIA-SPOT	Traffic smoothing using adaptive signal control	

TABLE III: V2X based congestion mitigation

Research Work	Authors	Disadvantage	Simulation Tool
V2X-based traffic congestion recognition and avoidance	Wedel, Jan W., Björn Schünemann, and Ilja Radusch [12]	May not work in case of high density traffic due to data drops	VsimRTI
Reducing traffic jams via VANETs	Knorr, Florian, Daniel Baselt, Michael Schreckenberg, and Martin Mauve [22]	May not work in case of high density traffic	JiST/SWANS
Real-time traffic congestion management and deadlock avoidance for vehicular ad hoc networks	Hussain, Syed Rafiul, Ala Odeh, Amrut Shivakumar, Shalini Chauhan, and Khaled Harfoush [25]	No estimate of algorithm performance for different levels of V2X penetration	Self built using Visual Studio 2010
Increased traffic flow through node-based bottleneck prediction and V2X communication	Backfrieder, Christian, Gerald Ostermayer, and Christoph F. Mecklenbräuker [26]	No estimate of algorithm performance for different levels of V2X penetration	TraffSim

Similarly, everywhere in the Netherlands, ITS solutions are heavily applied for congestion management and control. Traffic is constantly monitored by the Dutch traffic control center by means of cameras and speed loops. The Dutch Traffic Control also uses UTOPIA (Urban Traffic Optimization by Integrated Automation)-SPOT (System for Priority and Optimization of Traffic) [19], an adaptive traffic control system responsible for automatically determining and implementing optimum management strategies. Table II summarizes the existing traffic congestion mitigation strategies in both Singapore and Eindhoven.

One issue with all of the above mentioned congestion avoidance techniques is that they come into effect only after a congestion situation has transpired. Any mitigatory solution cannot be implemented on a moment's notice and, moreover, it takes a certain amount of time before the congestion dissipates and traffic becomes smooth again. Therefore, the focus of numerous researchers is to come up with solutions that are more proactive, but are based on data collected from practical sources (loop detectors, cameras, V2X, etc). In the next subsection, we will elaborate on the congestion mitigation strategies that rely on a V2X infrastructure.

C. V2X based traffic congestion mitigation

V2X communications has the potential to improve traffic efficiency considerably [20]. Implementation of a pervasive V2X infrastructure will allow vehicle and traffic management centers to access copious amounts of real-time traffic data that will encourage the conception of more sophisticated congestion mitigation solutions. In academia, a lot of effort is being put into developing V2X-reliant optimal route guidance and navigation solutions to combat congestion. Table III provides a summary of the work currently being done along with the advantages, disadvantages and their choice of simulation tool. In the remainder of this section, we will provide more details about the different studies.

Wedel et al. [12] conceptualize the application of V2X for real-time information sharing about the traffic conditions. The technique involves applying the Djikstra algorithm [21] by viewing intersections and road segments as nodes and edges. However, this strategy comes into effect only when a congestion situation has already occurred. In order to simulate the effectiveness of this algorithm, the authors used VsimRTI, a simulation architecture that is inspired by IEEE Standard for Modelling and Simulation (M&S) High Level Architecture. The results show that application of this approach leads to a decrement in travel time by almost 50%, as V2X penetration rate reaches 80% and higher.

In another congestion avoidance approach introduced by Knorr et al. [22], advisories are provided to the drivers to maintain a larger gap to the preceding vehicle, in case a congestion is detected. This helps in reduction of perturbations that add to the congestion. For the purpose of testing, both traffic and communication have been modeled in the JiST/SWANS simulator [23]. However, the approach proposed in [22] may not be effective in highly congested traffic situations because the message dissemination is carried out by means of periodic broadcasts. This may lead to a broadcast storm and collisions when multiple vehicles are broadcasting all together [24].

Syed Rafiul Hussain et al. [25] have introduced a new protocol named COMAD (COngestion Management And Deadlock avoidance). Approaching vehicles broadcast periodic messages indicating their arrival to a particular traffic intersection, which are then processed to evaluate the average queue length and waiting time. In case of a potential congestion, all the neighbouring intersections are informed so that they advise alternate routes to approaching vehicles, to avoid exacerbation of the congestion.

Another approach for congestion avoidance aims to leverage data from V2I communication, to predict traffic congestion [26]. The novelty of this work lies in the usage of traffic prediction algorithms to identify the possibility of a future congestion, in the case of which, alternative routes for approaching vehicles can be calculated. Subsequently I2V com-

TABLE IV: Simulation tools utilized in GLOSA research

Research Work	Simulation Tool	Simulation shortcomings
Impact of signal phasing information accuracy on green light optimized speed advisory systems [8]	Traffic simulation - **VISSIM** Communication simulation - **VISSIM Car2X**	Car2X has been discontinued by VISSIM
Performance study of a Green Light Optimized Speed Advisory (GLOSA) application using an integrated cooperative ITS simulation platform [33]	Traffic simulation - **SUMO** Communication simulation - **JiST/SWANS**	Only fixed time traffic signal can be modelled
Predictive driving strategies under urban conditions for reducing fuel consumption based on vehicle environment information [32]	Vehicle and predictive trajectory simulations in **MATLAB**	No traffic simulation and perfect communication assumed

munication is used for communicating the alternative routes to approaching vehicle.

However, in both [25] and [26], it has not been investigated how different penetration levels of V2X technology would affect the protocols and algorithms as all vehicles are assumed to have V2X technology. This is because the simulation environment considered in each approach lacks the capability of carrying out realistic network simulations. Hussain et al. [25] assume ideal PHY and MAC layer in the simulations, therefore, the effect of path loss, interference and packet collisions have not been taken into account as well.

In the next section, we go into greater detail behind the conception of GLOSA and the studies that have been carried out to prove the effectiveness of this idea.

D. Green Light Optimized Speed Advisory

In this chapter, we aim to simulate the V2X enabled Green Light Optimized Speed Advisory (GLOSA), and investigate the benefits that it can bring to traffic flow efficiency. However, before analysing the results, we present a brief review of the research carried out in developing GLOSA as well as the simulation tools used for testing. Table IV summarizes representative research studies on GLOSA, the simulation tools applied in those studies, and the shortcomings of each tool.

The concept of GLOSA was first conceived in 1983, when Volkswagen [28] introduced the Wolfsburger Welle. The idea was to communicate speed advisory using infrared technology. However, the project was discontinued due to technical issues and lack of commercial acceptance. Interest in GLOSA resurfaced when the IEEE 802.11p communication protocol got introduced, as this opened up a new avenue for data exchange. Some of the projects that capitalized on DSRC for implementation of GLOSA were the Travolution project [29], simTD [30] and PREDRIVE C2X [31].

Raubitschek et al. [32] investigated how fuel consumption can be reduced if the traffic velocity profile dynamics can be pre-adjusted based on an upcoming traffic event, such as a traffic signal. Simulations and real life experiments showed a reduction of 13% in fuel consumption (and CO2 emissions). However, only a single traffic light was investigated and the velocity adjustments are made assuming vehicles do not influence each other which is highly unlikely.

Katsaros et al. [33] tested a GLOSA-like scenario in a two-intersection model developed in SUMO. The authors incorporate JiST/SWANS to carry out network simulations and applied the Fraunhofer VSimRTI to enable an online interface between traffic and communication simulation models. The results show that higher GLOSA penetration rates provide more benefits in terms of fuel consumption and traffic congestion. Also, the optimal activation distance where the GLOSA application should advise the driver, is found to be approx. 300m from the traffic lights. Even though a more accurate communication model was utilized, analysis was done for only a fixed-time traffic signal.

In order to make the simulations more realistic, Stevanovic et al. [8], take into consideration the queue discharge time in their calculation of the optimized speed advisory. However, the communication simulations were carried out using the Car2X module of VISSIM, which is no longer an available feature.

Weisheit et al. [34] and Bodenheimer et al. [35] are one of the few research studies that have attempted to implement GLOSA for an adaptive traffic light scheduling policy. However in both cases, before an advisory is broadcast, the GLOSA system will need to predict the dynamically assigned phase durations, which may or may not be accurate. In the case of GLIDE, cycle times and green times are calculated for each cycle based on the volume of traffic observed in the previous cycle and this new time does not change for the entire cycle duration. Therefore, it is possible to know the phase change time in advance. Since we are modelling the GLIDE system, our study will not be afflicted by the afore-mentioned predicament.

In summary, as can be observed from sections II-C and II-D, a number of traffic congestion strategies have been conceived that depend heavily on data acquired or disseminated using V2X communication. In order to test their approaches and algorithms, the researchers have resorted to either a self-developed simulation tool or one of the tools referred to in Section II-A. However, as the research typically concentrated on either the traffic or the communication aspect, detailed modeling has been carried out only for the specific area of interest. In the few studies where both the traffic and communications aspects were modeled, the simulation environment lacked the capability to model extra specifics such as adaptive traffic signals or various levels of V2X penetration. Therefore, we decided to develop a simulation framework that allows us to address these various factors in the testin of GLOSA. GLOSA has been modeled based on the algorithm developed in [8], and we analysed how various variables including the V2X penetration rate, traffic flows, and presence of both fixed time and adaptive traffic signals (GLIDE) affect its performance.

III. Simulator Design

In this section, we describe the simulation design and architecture. Fig 1 shows the structure of the simulator plat-

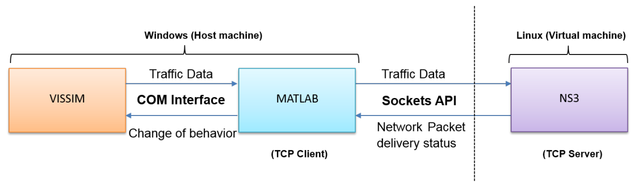


Fig. 1: Block diagram of the simulation environment.

form. VISSIM and MATLAB communicate with each other via VISSIM's COM interface, which enables access to most attributes of the traffic simulation such as vehicle speeds, positions, signal phase information, etc. through MATLAB. Both VISSIM and MATLAB were installed on a Windows OS, since VISSIM only runs on a Windows platform. On the other hand, NS3 has been developed for Linux. To couple VISSIM/MATLAB with NS3, we setup a Linux virtual machine, installed NS3 on it and linked the host machine (with Windows) to the virtual machine via a virtual network. We then applied sockets API for communication of data between MATLAB and NS3.

However, in order to design an online simulator for V2X operations, one needs to take care of several other considerations which have been listed down as follows:

- Time synchronization between a continuous time simulation environment (VISSIM) and a discrete-event simulator (NS3)
- Dynamic addition and removal of nodes in NS3
- Choice of appropriate mobility model in NS3

The following sub-sections elaborate on the strategies that have been applied to address the afore-mentioned considerations.

A. Time synchronization between a continuous time simulation environment and a discrete-event simulator

In order to synchronize the three simulators, TCP/IP blocking sockets have been utilized. Once NS3 finishes its initial configuration, it enters the simulation phase upon which the code is blocked from proceeding, at the zeroth second. Subsequently, the traffic simulations are triggered via a COM API function. As soon as the first group of vehicles enter the network their positions are relayed to NS3 along with the time at which they enter the network. This allows scheduling a position update event in the network simulator at the same virtual time as VISSIM. Simultaneously at this point, VISSIM enters a blocked state and needs to wait till NS3 reverts back with the results of a communication simulation. Blocking events are scheduled every simulation second for obtaining data from MATLAB which ensures that at every subsequent second of VISSIM virtual time, appropriate vehicle data is communicated to NS3. A flowchart describing this process has been presented in Appendix A.

B. Dynamic addition and removal of nodes in NS3

In NS3, new nodes cannot be created nor existing nodes be destroyed until the end of the simulations. In order to work around this, a fixed number of nodes are created during the NS3 configuration phase without any virtual sockets attached. Sockets are only attached to the appropriate number of nodes during runtime, as there are vehicles in the network. In order to characterize a vehicle in NS3, a *Vehicle Node* structure is created with the following fields:

- `Ptr<Node> veh_node` : Smart pointer to the NS3 node object
- `Ptr<Socket> veh_socket` : Smart pointer to the NS3 socket attached to the node
- `int veh_number` : Integer vehicle number
- `bool in_use` : Boolean True or False to indicate if node is currently in use

A vector of such *Vehicle Node* structure objects are created and each NS3 node is then loaded onto the `veh_node` member of the object. Every time a new vehicle enters the network it will be associated with a *Vehicle Node* object, which is currently not "in use", and a socket will be attached. Once a *Vehicle Node* is active, only its mobility model is updated every simulation second. When the vehicle leaves the network, communication is disabled by closing the socket and setting the `in_use` parameter to *False*. In order to use the same node object for a different vehicle, we bind the socket to an address and re-enable *Recv* calls on it. Algorithm 1 presents the pseudo code to achieve the aforementioned process:

C. Choice of appropriate mobility model in NS3

In order to model the mobility of the vehicles accurately, we chose the Waypoint Mobility Model in NS3. To provide waypoints in an online manner, we decided to run VISSIM, one simulation step in advance, as has been described in [36]. This ensured that both origin and destination waypoints are always available to simulate node mobility.

IV. Simulation Setup

A. Traffic Network

For the purpose of our study of GLOSA, we have modelled an intersection in Singapore as shown in Fig 2 and one in Eindhoven, Netherlands, Fig. 3. There is no specific reason to choose these two particular intersections, apart from the purpose of demonstrating the applicability of the simulation tool to any traffic network, for both left hand drive (Singapore) and right hand drive (Eindhoven) traffic. The traffic simulation has been carried out over the entire network depicted in Fig 2 and 3. However, data regarding fuel consumption and queue length have been collected from within the nodes marked with black borders. We have not modelled traffic signals on the three minor intersections in the north-west, north-east and the south-east approaches of the Eindhoven network. We assume that there is a thoroughfare all the way from the start of the links, as we wanted the approaches to the intersection to be at least 200 metres in length. All the traffic flow values referred to in Fig 5, 6 and 7 correspond to the total vehicle flow on all the links inside the nodes.

We also assume that all traffic signal heads in the two intersections have a Road Side Unit attached to them. These RSUs are broadcasting at 1Hz, the signal head location, current phase, and the remaining phase time of the traffic signals.

Algorithm 1 Dynamic addition and removal of nodes

Require:
A vector $[N_i]$, $i = 1, 2, \ldots, n$, of pre-configured NS-3 nodes
A vector $[Vnode_m]$, $m = 1, 2, \ldots, n$, of $Vehicle\_Node$ structures

Initialize:
  $[Vnode_m].veh\_node \leftarrow [N_i]$
for t = 1 to T **do**
  Receive list of vehicles $[VL_t]$ and their positions from VISSIM
  for $v \in [VL_t]$ **do**
    if $v \notin [Vnode_m]$ **then**
      for k = 1 to n **do**
        if $Vnode_k.in\_use = False$ **then**
          $Vnode_k \leftarrow v$; ▷ Record veh_number and set in_use to $True$.
          if $veh\_socket \Rightarrow NULL$ **then**
            Initialize veh_socket with NS-3 $socket$ object;
            break;
          else
            Bind address to veh_socket and re-enable $Recv$ flag;
            break;
          end if
        end if
      end for
    else
      Update mobility model of v using its current position received from VISSIM;
    end if
  end for
  for $v_n \in ([VL_t] \cap [Vnode_m])^c$ **do**
    Close veh_socket of v_n;
    Set in_use of v_n to $False$;
    Set veh_number of v_n to 0;
  end for
end for

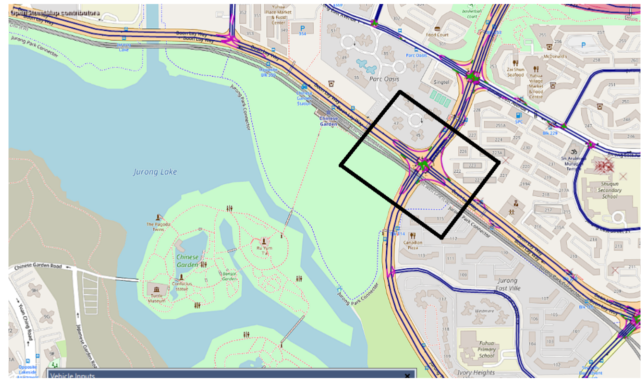


Fig. 2: VISSIM representation of the traffic network in Singapore

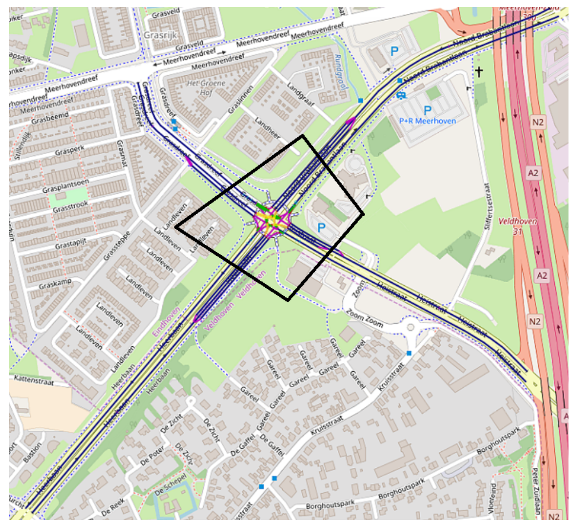


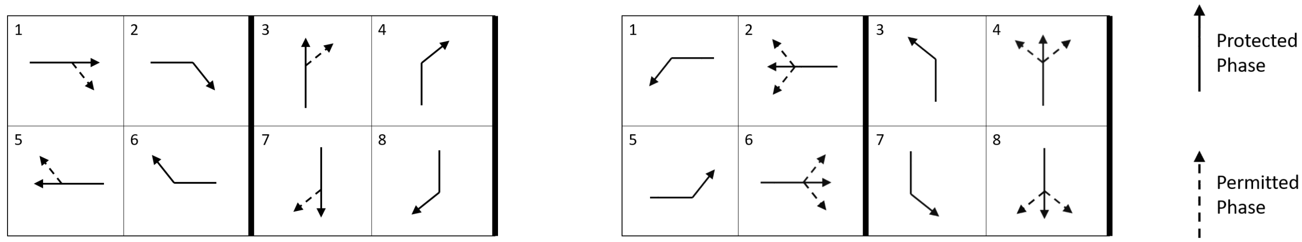
Fig. 3: VISSIM representation of the traffic network in Eindhoven, Netherlands

Each intersection has four approaches. For the intersection in Singapore, the length of the links for each approach to intersection 1 is 603.5 meters (East to West Link), 706 meters (West to East Link), 250 meters (North to South Link) and 296 meters (South to North Link) respectively. Similarly, the length of links on the Eindhoven intersection is 720 meters (South west to North East), 560 meters (North East to South west), 350 meters (North West to South East) and 553 meters (South East to North West) respectively. The length of the links is important, since the activation distance (distance at which a vehicle first receives information from the RSU) has strong impact on the effectiveness of GLOSA [33].

The information broadcast from a particular signal head is only relevant when the vehicle is on the link served by the traffic signal. Therefore, even if the vehicle is within range, and consequently receives a packet, those packets will be discarded if the vehicle is not on the corresponding link. In order to encode the association between a traffic signal and its corresponding link, we create a mapping between the link number and the MAC address of the RSU attached to the signal head.

B. Signal Timing

1) Signal Timing for the Singapore Intersection: Since the Singapore traffic signal system is goverened by the Green Link Determining System (GLIDE), we decided to model the GLIDE algorithm following the approach of Daizong et al. [37]. They developed a SCATS-based API plug-in for the Paramics traffic simulator derived from GLIDE outputs files provided by the Land Transport Authority of Singapore (LTA). The base cycle time is chosen to be 100 seconds and the signal phase plan has been illustrated in Fig. 4(a). New cycle times is generated by adding/subtracting a few seconds to the previous cycle time with the maximum being 6 seconds. However, if for three consecutive cycles, the cycle time is increased/decreased by 6 seconds, then the maximum switches to 9 seconds. In Singapore, the maximum value the cycle time can be increased



(a) Singapore Phase Plan **(b)** Eindhoven Phase Plan

Fig. 4: Ring barrier diagrams for Singapore and Eindhoven

to is 140 seconds, while the minimum is 60 seconds. For more details on the GLIDE emulation algorithm and the signal phase split choices, we refer the reader to [37].

2) Signal Timing for the Eindhoven intersection: We assume that the Eindhoven traffic intersection is governed by a fixed-time signal policy. A Protected-Permissive Left-Turn Phasing has been considered, as shown in Fig 4(b). The fixed cycle time has been set to 100 seconds while the individual phase times are 15 seconds, 35 seconds, 15 seconds and 25 seconds for Phase 1&5, Phase 2&6, Phase 3&7 and Phase 4&8 respectively. For both the signal groups, the amber time is 3 seconds with a 2 second all-red between change of phase between the groups.

We compute the GLOSA advisories from the timings of Signal phases 2&6 and 4&8, since the left turn is permissive, and the straight going vehicles will be the main beneficiaries of GLOSA.

C. Fuel consumption modelling

We applied the VISSIM node evaluation module for determining fuel consumption. The module utilizes the same formulas that are present in the traffic signal system simulation and optimization software TRANSYT 7-F for calculating fuel consumption of vehicles [38], [39]. TRANSYT 7-F allows the optimization of signal times with respect to delay, number of intersection stops, and fuel consumption. The underlying model of fuel consumption is a function of: (1) Total travel (vehicle-mi/hr), (2) Total delay (vehicle-hr/hr), (3) Total stops (full stops/hr) and (4) Free speed on each link (mph).

The model was calibrated on data of fuel consumption gathered by the Oak Ridge National Laboratory of the U.S. Department of Energy [40] in 1985. The tests combined laboratory and on-road experiments with 15 vehicles and the data was collected as a function of both acceleration and velocity.

D. Communication Simulation

For the purpose of simulation, we have utilized NS3 because of the justifications as elaborated in [41]. In the network simulations, the signal head RSU node is programmed to broadcast 500 byte long messages at 1 Hz (1 messages/sec). Four different combinations of transmit power, energy detection threshold, and data rate have been chosen to incorporate variation in the activation distance and analyse the effects on fuel consumption. Table V captures four different settings of the afore-mentioned communication parameters, associated with an increasing activation distance.

TABLE V: Combinations of communication parameters

Parameter Table	
Communication Parameters	Parameter Value
Transmit Power Energy Detection Threshold Data Rate	12 dBm -70 dBm 9 Mbps
Transmit Power Energy Detection Threshold Data Rate	15 dBm -75 dBm 9 Mbps
Transmit Power Energy Detection Threshold Data Rate	23 dBm -87 dBm 6 Mbps
Transmit Power Energy Detection Threshold Data Rate	28.8 dBm -95 dBm 6 Mbps

V. Simulation Results

In order to determine the efficacy of GLOSA, we conducted simulations of 800 seconds duration for the Singapore intersection, and 600 seconds duration for the Eindhoven intersection. We added an extra 200 seconds to the simulation time on the Singapore intersection to generate historical data for the GLIDE algorithm. The minimum and maximum advisory that GLOSA can hand out to a vehicle is assumed to be 20 Km/Hr and 100 Km/Hr, respectively. While there is no minimum speed limit, we chose the lowest assigned speed to be 20 Km/Hr so that a slow speed does not lead to a congestion. Furthermore, we are interested to to assess the effectiveness of GLOSA for different traffic volumes. To this end, we varied the vehicle densities to create conditions for mild to high congestion. We also performed simulations for V2X penetration rates of 0%, 10%, 20%,...., 100%.

For both the Singaporean and Dutch intersections, it can be observed that for low RSU power values and high data rates (hence low activation distance), the effects of GLOSA are not favorable for either low or high density traffic. These results exhibit a trend similar to the results of [33], in which the correlation between GLOSA effectiveness and activation distance has been analysed. In addition, for the Singaporean network, the negative effects are exacerbated due to lack of information about the cycle time in the subsequent traffic signal cycles, for both low and high power RSUs. This affects vehicles that cannot make it through the green phase of the current cycle

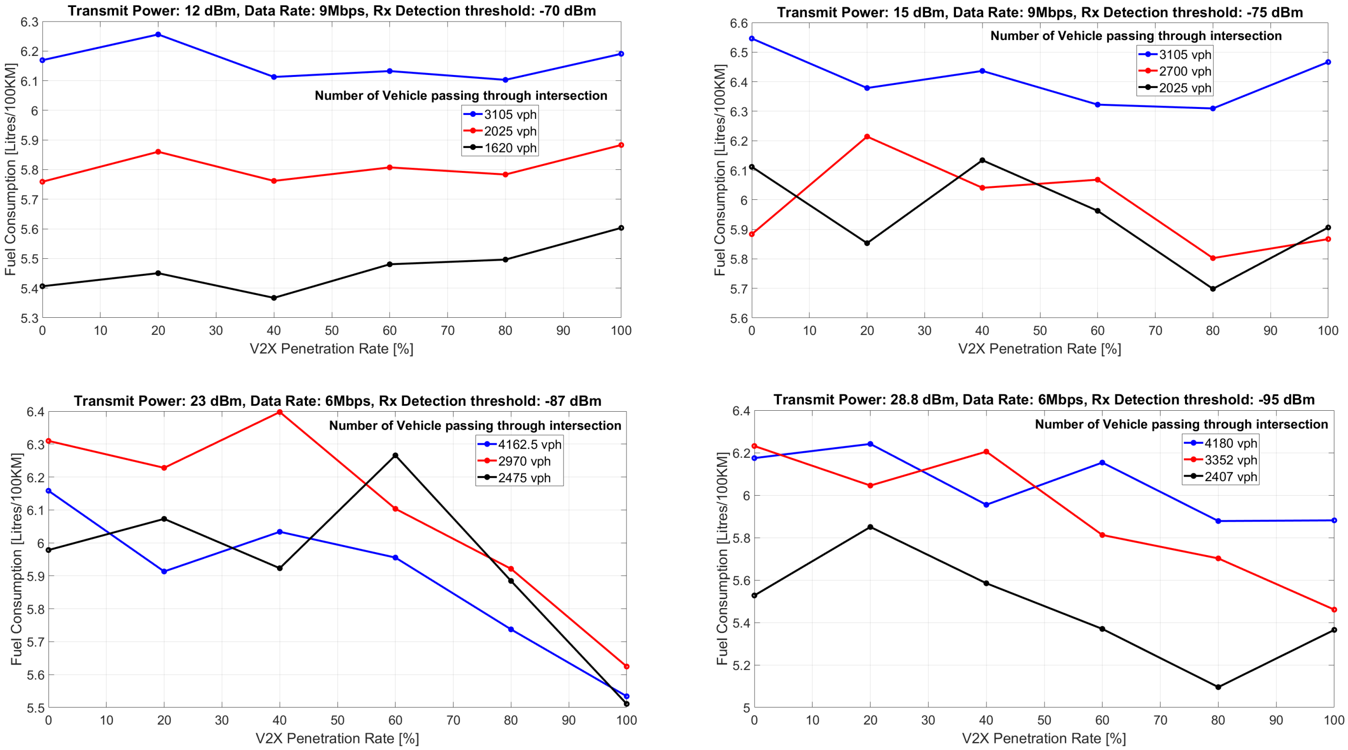


Fig. 5: Fuel Consumption for the Singapore Intersection

and have to cross in the green phase of the next cycle, but have calculated the advisory speed based on the phase timings of the current cycle. By increasing the RSU power and reducing both the data rate and the energy sensitivity of the receiver, the activation distance increases, and consequently GLOSA performs better even with high traffic volumes. However, the decrease in fuel consumption and queue length even for higher activation distances is not consistent for the Singapore network due to the afore-mentioned restrictions posed by the GLIDE system.

Each curve in Fig. 5 and 6 shows the fuel consumption for various V2X penetration rates and traffic volumes. For the Singaporean intersection in Fig. 5, with a transmit power of 23dBm, data rate of 6 Mbps, and receiver sensitivity of -87 dBm, the fuel reductions from no V2X to full V2X penetration are approximately 3%, 12% and 4.7% for vehicle densities of 2500, 3000 and 4000 vehicles per hour approximately. For a transmit power of 28.8 dBm, data rate of 6 Mbps and receiver sensitivity of -95 dBm the fuel consumption minimization is approximately 2.5%, 11% and 5.3% for vehicle flows of 2400, 3300 and 4100 vph. For each set of communication parameters, the fuel consumption value is different for the no–V2X scenario, since the traffic simulations have been conducted with a different random seed each time. In the case of the Eindhoven intersection in Fig 6, we can see that for a transmit power of 23 dBm, data rate of 6 Mbps and energy detection of -87 dBm, the fuel consumption decrements are approximately 18%, 12% and 10.5% for densities of 2000, 2700 and 4400 vehicles per hour, while for a power of 28.8 dBm, data rate of 6 Mbps and sensitivity of -95 dBm the decrements are in the order of 16%, 18% and 9% for 2000, 2400 and 4200 vehicles per hour approximately.

As mentioned earlier in section IV-A, the vehicle flows refer to the flows on all the links inside the polygon node in Fig 2 and Fig 3. The vehicle densities have been set randomly between 2000 and 4000 vehicles per hour to analyze the effects of GLOSA for mild to high traffic congestion. Therefore, it can be observed that GLOSA performs much better for a fixed time traffic signal control than for a vehicle actuated control system. In the case of the fixed time traffic signal, we can observe that for low and medium density traffic, the reduction in fuel consumption is higher than for high density traffic. This can be mainly attributed to the fact that there is a greater proportion of vehicles that is provided with a speed advisory in the lower range of speeds, i.e., 20 Km/Hr–40 Km/Hr. These speeds are not optimal from the point of view of fuel consumption, and due to a greater distribution of the slower vehicles, they are in a better position to influence the traffic. Consequently, the overall flow of traffic becomes slower and for high density traffic, the fuel consumption benefits are comparatively lower. However, the same justification is not applicable to the Singaporean network, where the signals are governed by the vehicle actuated GLIDE system. In this case, we can see that for low density traffic, the fuel consumption reduction is the lowest. This is due to the fact that if a reduced vehicle flow is observed, GLIDE tends to shorten the cycle time and changes the split plan in order to distribute the degree of saturation evenly across all links. This mostly leads to a longer red and a shorter green phase. Due to the lengthening of red phase timings in each cycle, the advisory that is calculated using the previous cycle is not sufficient for the vehicle to arrive at the intersection at the next green

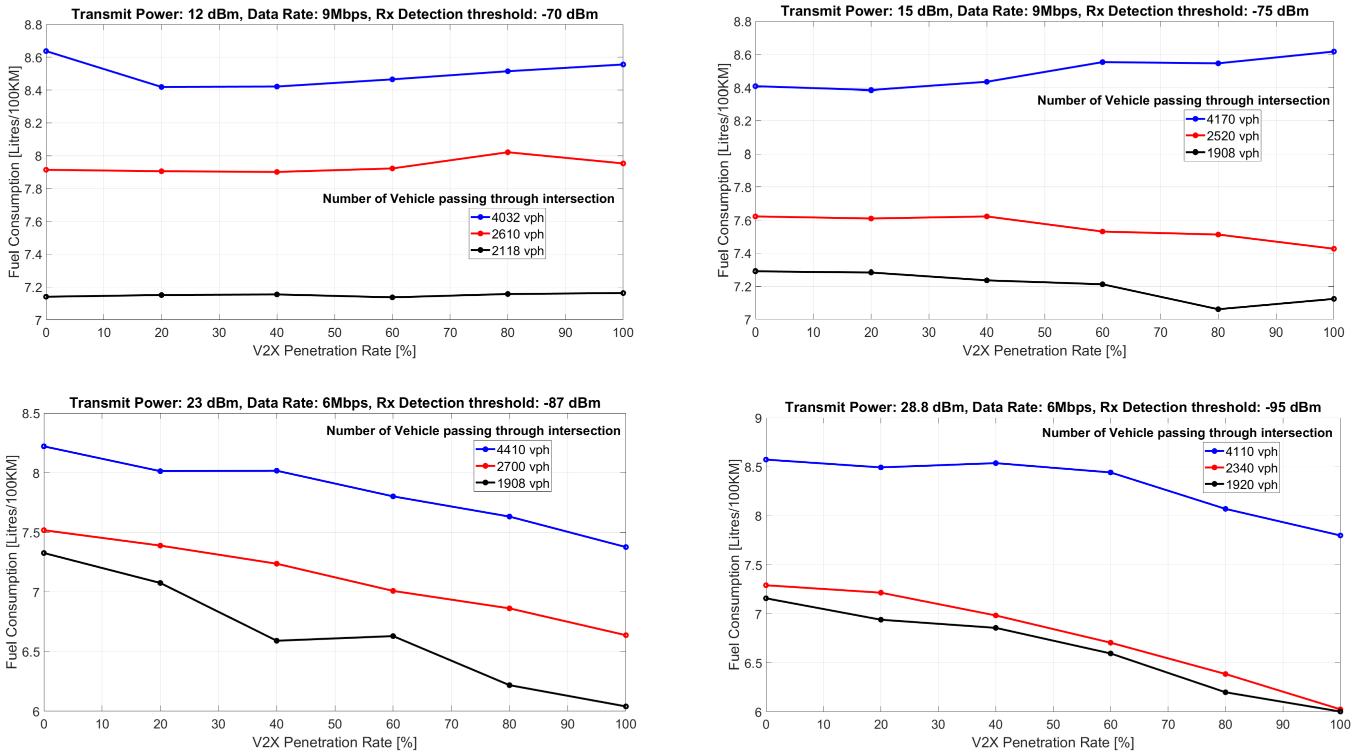
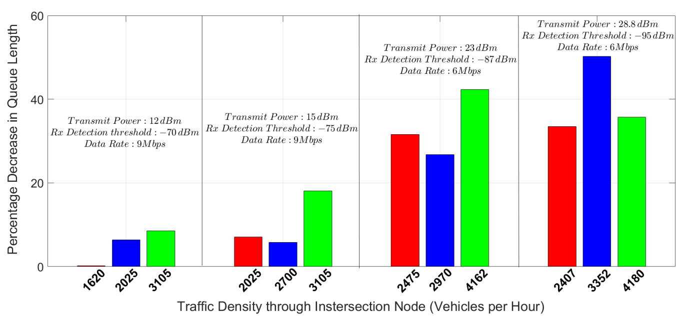
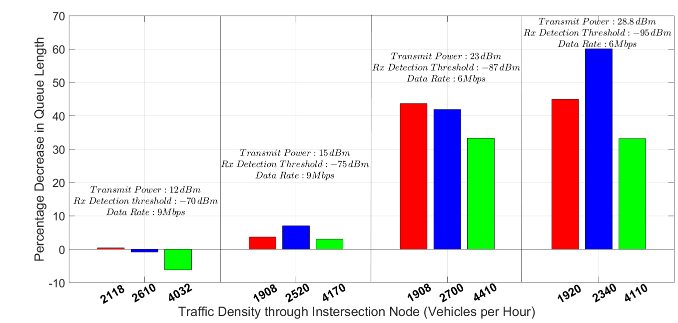


Fig. 6: Fuel consumption for the Eindhoven intersection



(a) Queue length statistics on the Singapore network.



(b) Queue length statistics on the Eindhoven network.

Fig. 7: Queue length Reduction in both networks due to application of GLOSA.

phase. Therefore, most of the vehicles, even after receiving an advisory, are forced to come to a stop at the intersection and start from zero once the lights turn green. As a result, this leads to greater fuel consumption. However, for medium and high density traffic, the cycle and split times either stay the same or the red phase time will be reduced in the the next cycle, resulting in the vehicles able to make it through the intersection without having to stop. For high density traffic, the reduction in fuel consumption is again less than for medium density for the same reason as for fixed time traffic signal. For more comprehensive results, the traffic model can be calibrated with the relevant traffic flow data, for any road network of interest. In addition, one can also accurately model the V2X communication channel characteristics by integrating a realistic physical layer model into NS-3, as has been shown in [42].

In addition to the fuel consumption, we have also shown decrements in queue length due to the implementation of GLOSA in Fig 7(a) and 7(b). Again, it can be seen that for weaker radio configurations (lower activation distances), the decrements are not very significant. For the Eindhoven intersection in Fig 7(b), it can be observed that implementation of GLOSA is actually increasing queue length. For fixed traffic signals, we see that the queue length reductions for low, medium and high density traffic are more or less comparable, differently from fuel consumption. Even if a slower speed is assigned to a larger proportion of vehicles (in the high density case), GLOSA ensures that the vehicles arrive at the intersection at a green phase. Therefore, the reduction in queue length is bound to happen.

Furthermore, from Fig. 5, 6 and 7, it can be seen that GLOSA performances for the 23 dBm RSU transmit power and 28.8 dBm transmit power are comparable. This complies with the conclusion that was drawn by [33], that beyond an optimal activation distance, the benefits of GLOSA saturates. Therefore, we can conclude that if GLOSA is to be implemented using V2X technology, it is necessary that optimum transmission power of the traffic light RSU is established first. The optimum value will depend on a number of factors including the length of the road, the topology of the road network, the configuration of the static environment and the receiver sensitivity. Furthermore, the effectiveness of GLOSA will also depend on the traffic flow at various times of the day, since traffic gridlocks may lead to reduction in manoeuvring space and increased load on the bandwidth. Since it is not feasible to establish the optimal infrastructure placement for all traffic conditions using only field tests, simulations become even more necessary.

VI. Conclusion and Future Work

In this chapter, we aimed to explore a simulation approach to analyze V2X applications in realistic traffic scenarios, illustrated by the example of V2X-enabled GLOSA. To this end, we chose to simulate the application of GLOSA for two intersections in order to explore various parameters that one can influence and evaluate using the simulation tool. Specifically, we considered the following parameters:

1) Representation of a realistic road network,
2) Modelling of fixed and vehicle actuated traffic signals (GLIDE) in this case,
3) Modelling a VANET with different communication parameters (transmit power, receiver sensitivity, data rate, etc.) for RSU and OBUs,
4) Ability to incorporate a realistic path loss models,
5) Ability to measure traffic performance metrics such as fuel consumption,
6) Analyze the effects of multiple penetration levels of V2X technology
7) Study the effects of the different V2X protocols.

From the simulations, we observed that the results obtained concur with work done on GLOSA by researchers previously. In addition, the results also indicate that the performance of GLOSA strongly depends on communication parameters heavily. Consequently, the selection of optimal parameters is highly conducive to the success of GLOSA. In most of the previous simulation attempts, the researchers focused on accurately modelling either the traffic component or the communication component, of a V2X application since both aspects are different fields of study. To address this shortcoming, we have integrated a realistic traffic simulator with a network simulator, in order to bridge the gap between the two disciplines. In the future, we intend to simulate more applications of V2X, along with integrating more realistic channel models. Such an approach would enable more accurate simulations of V2X applications with a much more accurate model of the V2V physical layer characteristics.

References

[1] Cohn, Nick. "TomTom Traffic Index: Toward a Global Measure." Proceedings of ITS. 2016.

[2] Levy, Jonathan I., Jonathan J. Buonocore, and Katherine Von Stackelberg. "Evaluation of the public health impacts of traffic congestion: a health risk assessment." Environmental health 9.1 (2010): 65

[3] Barth, Matthew, and Kanok Boriboonsomsin. "Real-world carbon dioxide impacts of traffic congestion." Transportation Research Record: Journal of the Transportation Research Board 2058 (2008): 163-171.

[4] Keong, Chin Kian. "The GLIDE system—Singapore's urban traffic control system." Transport reviews 13.4 (1993): 295-305.

[5] Aydos, J. Carlos, and Andrew O'Brien. "SCATS ramp metering: strategies, arterial integration and results." Intelligent Transportation Systems (ITSC), 2014 IEEE 17th International Conference on. IEEE, 2014.

[6] Chin, K. K., and C. W. Lee. "TrafficScan-bringing real-time travel information to motorists." Land Transport Authority, Singapore (2009): 7-14.

[7] Chia, Eng Seng. "Engineering Singapore's Land Transport System." Complex Systems Design & Management Asia. Springer, Cham, 2015. 99-109.

[8] Stevanovic, Aleksandar, Jelka Stevanovic, and Cameron Kergaye. "Impact of signal phasing information accuracy on green light optimized speed advisory systems." Transportation Research Board 92nd Annual Meeting. 2013.

[9] Choudhury, Apratim, et al. "An Integrated Simulation Environment for Testing V2X Protocols and Applications." Procedia Computer Science 80 (2016): 2042-2052.

[10] Weiß, Christian. "V2X communication in Europe. From research projects towards standardization and field testing of vehicle communication technology." Computer Networks 55.14 (2011): 3103-3119.

[11] Hafner, M. R., et al. "Automated vehicle-to-vehicle collision avoidance at intersections." Proceedings of world congress on intelligent transport systems. 2011.

[12] Wedel, Jan W., Björn Schünemann, and Ilja Radusch. "V2X-based traffic congestion recognition and avoidance." Pervasive Systems, Algorithms, and Networks (ISPAN), 2009 10th International Symposium on. IEEE, 2009.

[13] Schünemann, Björn. "V2X simulation runtime infrastructure VSimRTI: An assessment tool to design smart traffic management systems." Computer Networks 55.14 (2011): 3189-3198.

[14] Lochert, Christian, et al. "Multiple simulator interlinking environment for IVC." Proceedings of the 2nd ACM international workshop on Vehicular ad hoc networks. ACM, 2005.

[15] Rondinone, Michele, et al. "iTETRIS: a modular simulation platform for the large scale evaluation of cooperative ITS applications." Simulation Modelling Practice and Theory 34 (2013): 99-125.

[16] Noori, Hamed. "Realistic urban traffic simulation as vehicular adhoc network (vanet) via veins framework." 12th Conference of Open Innovations Framework Prgramm. FRUCT. 2012.

[17] Wang, Shie-Yuan, and Chih-Che Lin. "NCTUns 6.0: a simulator for advanced wireless vehicular network research." Vehicular Technology Conference (VTC 2010-Spring), 2010 IEEE 71st. IEEE, 2010.

[18] Goh, Mark. "Congestion management and electronic road pricing in Singapore." Journal of Transport Geography 10.1 (2002): 29-38.

[19] Studer, L., Ketabdari, M., and Marchionni, G. (2015). Analysis of adaptive traffic control systems design of a decision support system for better choices. J Civil Environ Eng, 5(195), 2.

[20] Baldessari, Roberto, et al. "Car-2-car communication consortium-manifesto." (2007).

[21] Bondy, John Adrian, and Uppaluri Siva Ramachandra Murty. Graph theory with applications. Vol. 290. London: Macmillan, 1976.

[22] Knorr, Florian, et al. "Reducing traffic jams via VANETs." IEEE Transactions on Vehicular Technology 61.8 (2012): 3490-3498.

[23] Barr, Rimon, Zygmunt J. Haas, and Robbert Van Renesse. "Jist: Embedding simulation time into a virtual machine." EuroSim congress on modelling and simulation. 2004.

[24] Milojevic, Milos, and Veselin Rakocevic. "Distributed road traffic congestion quantification using cooperative VANETs." Ad Hoc Networking Workshop (MED-HOC-NET), 2014 13th Annual Mediterranean. IEEE, 2014.

[25] Hussain, Syed Rafiul, et al. "Real-time traffic congestion management and deadlock avoidance for vehicular ad hoc networks." High Capacity Optical Networks and Enabling Technologies (HONET-CNS), 2013 10th International Conference on. IEEE, 2013.

[26] Backfrieder, Christian, Gerald Ostermayer, and Christoph F. Mecklenbräuker. "Increased Traffic Flow Through Node-Based Bottleneck Prediction and V2X Communication." IEEE Transactions on Intelligent Transportation Systems 18.2 (2017): 349-363.

[27] Backfrieder, Christian, Christoph F. Mecklenbrauker, and Gerald Ostermayer. ”TraffSim–A Traffic Simulator for Investigating Benefits Ensuing from Intelligent Traffic Management.” Modelling Symposium (EMS), 2013 European. IEEE, 2013.
[28] Zimdahl, W. ”Wolfsburger Welle–Ein Projekt der Volkswagen Forschung.” Wolfsburg, Volkswagen Forschung (1983).
[29] Braun, Robert, et al. ”TRAVOLUTION–Netzweite Optimierung der Lichtsignalsteuerung und LSA-Fahrzeug-Kommunikation.” Straßenverkehrstechnik 53 (2009): 365-374.
[30] Stübing, Hagen, et al. ”sim TD: a car-to-X system architecture for field operational tests [Topics in Automotive Networking].” IEEE Communications Magazine 48.5 (2010): 148-154.
[31] PRE-DRIVE C2X project: http:// www.pre-drive-c2x.eu
[32] Raubitschek, Christian, et al. ”Predictive driving strategies under urban conditions for reducing fuel consumption based on vehicle environment information.” Integrated and Sustainable Transportation System (FISTS), 2011 IEEE Forum on. IEEE, 2011.
[33] Katsaros, Konstantinos, et al. ”Performance study of a Green Light Optimized Speed Advisory (GLOSA) application using an integrated cooperative ITS simulation platform.” 2011 7th International Wireless Communications and Mobile Computing Conference. IEEE, 2011.
[34] Weisheit, T. ”Algorithmenentwicklung zur Prognose von Schaltzeitpunkten an verkehrsabhängigen Lichtsignalanlagen.” Tagungsband HEUREKA (2014).
[35] Bodenheimer, Robert, et al. ”Enabling GLOSA for adaptive traffic lights.” 2014 IEEE Vehicular Networking Conference (VNC). IEEE, 2014.
[36] Eichler, Stephan, et al. ”Simulation of car-to-car messaging: analyzing the impact on road traffic.” 13th IEEE International Symposium on Modeling, Analysis, and Simulation of Computer and Telecommunication Systems. IEEE, 2005.
[37] Daizong, Liu. Comparative evaluation of dynamic TRANSYT and SCATS-based signal control systems using Paramics simulation. Diss. 2003.
[38] Penic, Michael A., and Jonathan Upchurch. ”TRANSYT-7F: enhancement for fuel consumption, pollution emissions, and user costs.” Transportation Research Record 1360 (1992).
[39] Miller, P., and R. Narayanan. ”Microscopic traffic simulation/animation software applications in plnning level transportation decision making.” Compendium of Papers. District 6 Annual Meeting.Institute of Transportation Engineers. 2000.
[40] McGill, R. Fuel Consumption and Emission Values for Traffic Models. No. FHWA/RD-85/053. 1985.
[41] Choudhury, Apratim, et al. ”An integrated V2X simulator with applications in vehicle platooning.” Intelligent Transportation Systems (ITSC), 2016 IEEE 19th International Conference on. IEEE, 2016.
[42] Boeglen, Hervé, et al. ”A survey of V2V channel modeling for VANET simulations.” Wireless On-Demand Network Systems and Services (WONS), 2011 Eighth International Conference on. IEEE, 2011.

APPENDIX A
FLOW OF DATA AMONGST SIMULATORS