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Estimating the Traffic Impacts of Green Light Optimal Speed Advisory Systems Using Microsimulation

C. B. Masera, M. Imprialou, L. Budd, C. Morton

Abstract**—**Even though signalised intersections are necessary for urban road traffic management, they can act as bottlenecks and disrupt traffic operations. Interrupted traffic flow causes congestion, delays, stop-and-go conditions (i.e. excessive acceleration/deceleration) and longer journey times. Vehicle and infrastructure connectivity offers the potential to provide improved new services with additional functions of assisting drivers. This paper focuses on one of the applications of vehicle-to-infrastructure communication namely Green Light Optimal Speed Advisory (GLOSA). To assess the effectiveness of GLOSA in the urban road network, an integrated microscopic traffic simulation framework is built into VISSIM software. Vehicle movements and vehicle-infrastructure communications are simulated through the interface of External Driver Model. A control algorithm is developed for recommending an optimal speed that is continuously updated in every time step for all vehicles approaching a signal-controlled point. This algorithm allows vehicles to pass a traffic signal without stopping or to minimise stopping times at a red phase. This study is performed with all connected vehicles at 100% penetration rate. Conventional vehicles are also simulated in the same network as a reference. A straight road segment composed of two opposite directions with two traffic lights per lane is studied. The simulation is implemented under 150 vehicles per hour and 200 per hour traffic volume conditions to identify how different traffic densities influence the benefits of GLOSA. The results indicate that traffic flow is improved by the application of GLOSA. According to this study, vehicles passed through the traffic lights more smoothly, and waiting times were reduced by up to 28 seconds. Average delays decreased for the entire network by 86.46% and 83.84% under traffic densities of 150 vehicles per hour per lane and 200 vehicles per hour per lane, respectively.

Keywords**—**Connected vehicles, GLOSA, intelligent transportation systems, infrastructure-to-vehicle communication.

I. INTRODUCTION

RAPID urbanization has increased the level of vehicle ownership and inevitably road traffic volume. In spite of the fact that road transport has indubitable benefits to societies, it also imposes undesirable impacts on the social, economic and physical environment. The main externalities are congestion, traffic accidents and pollution [1]. Congestion resulting in interrupted traffic flow occurs when the demand for road space exceeds the road's capacity or road closures and maintenance work reduce highway capacity [2]. Thereby, an increment in the time spent on the road leads to delays, increased travel times and excessive acceleration and deceleration. In addition, congestion has an adverse impact on the physical environment. The more time a vehicle spends waiting at traffic lights, the more fuel it consumes and the more pollution it emits from its exhaust [3]. This is mainly due to excessive speed alterations, with frequent acceleration and deceleration required during periods of disrupted traffic flow at signalised control points. This is a serious problem. For instance, in 2016, road transport became the largest source of greenhouse gas emissions, accounting for 26% of total emissions, ahead of energy generation at 25% [4], [5]. Moreover, road transport is also responsible for 34% of CO_2 emissions which is mainly caused by passenger vehicles in use (i.e. petroleum and diesel) and longer travel distances [6].

Congestion leads to inefficiency in traffic performance. Interrupted road operations because of traffic congestion result in lower speeds, delays, and "stop-and-go" conditions leading to longer travel times and distances [7], [8]. To illustrate, the main mode of travel to work in the UK is the private car [9], [10]. Some 80% of kilometres travelled by passengers in the UK occurred in cars, taxis and vans in 2016, and around 83% in 2017. Correspondingly, the travelling time to work by cars increased by approximately 11 minutes from 2016 (27 minutes) to 2017 (38 minutes) [9], [10].

Intelligent transport systems employ technological advancements to minimise the adverse congestion impacts of road transport and improve mobility. These involve variable speed limit (VSL) systems, traffic demand management tools, optimised driving behaviour (i.e., improvements in traffic movement), promotion of public transport [11], and signal actuation and coordination with respect to traffic volumes [12]-[14]. Representing a junction between different opposing traffic flows, signalised intersections are zones of conflict [15], [16]. Henceforth, it can be said that the developments in communication and information technologies pave the way for connected vehicle (CV) applications. Connected vehicles provide promising improved functions and technological applications and their communication capabilities have the potential to change driver behaviour in a favourable way.

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Connected vehicles have the ability to exchange instantaneous traffic information among vehicles and between vehicles and infrastructure through vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication technologies, respectively. Therefore, having access to currently unavailable traffic information beforehand enables connected vehicles to adapt their behaviours according to traffic conditions. These behavioural changes, if adopted by a large proportion of vehicles, are expected to deliver benefits in traffic flow and vehicle emissions [17]. In this regard, a recent application of infrastructure-to-vehicle (I2V) communication, the Green Light Optimal Speed Advisory (GLOSA) system, is proposed to improve traffic flow through alleviating congestion on signalised road networks. In this system, rather than adapting the signal plan with respect to traffic demand, vehicles are coordinated with a fixed and predefined traffic signal timing and plan [13]. GLOSA systems enable vehicles (through proposing an "ideal" speed) to approach the downstream traffic signals with information on signal phasing and timing (SPaT) in order to pass through traffic signals smoothly without stopping. Such applications primarily aim to improve traffic flow by improving overall traffic efficiency in terms of minimal delays and waiting times. In this manner, identification of congestion-related problems and regions will help to determine the areas that need further improvements in the traffic stream. For example, due to the fact that drivers cannot predict the traffic signal phase in advance to their arrivals, signalised controlled points at intersections can be determined as the concern areas to alleviate congestion with smoothened traffic flow.

This study aims to estimate the impacts of GLOSA systems on road traffic performance in terms of average delays and waiting times at traffic signals by means of individually recommended optimal speeds. For being a recent application, connectivity-related data are not widely available that leads this study to be simulation-based. In addition, the objectives of this study are to develop and demonstrate an integrated microscopic traffic simulation environment for green light optimal speed advisory application, identifying potential benefits of this system, particularly on average delays and waiting times, and observing the alterations on the speed profiles of vehicles with and without this application. Thus, a control algorithm was developed to implement green light optimal speed advisory systems under the connected vehicle environment via an integrated microscopic simulation platform. It is more crucial and complicated to calculate and provide an optimal speed advisory to the vehicles arriving at the traffic signal during the red phase. The studies on recommending an optimal speed for a red phase is limited. However, the proposed control algorithm here is able to provide an optimal speed advisory for both green and red signal phases updated at every time step.

II. GREEN LIGHT OPTIMAL SPEED ADVISORY SYSTEMS

Green light optimal speed advisory is an infrastructure-to-vehicle (I2V) communication system in which the downstream signal controllers communicate with approaching vehicles to broadcast accurate and timely data on locations and timing phases of traffic lights [13], [18]. It is believed that using pre-defined timings and cycles in this application make it more effective than adaptive traffic lights because extending and adapting the phase durations according to in-demand traffic can create more conflicts in traffic flow and, therefore, additional delays [19]. For building the communication and exchanging data, different information and communication technologies can be used. Dedicated short-range communication (DSRC), Bluetooth, 3G and 4G are some examples.

Real-time signal status such as the current and future signal phasing data of the traffic light is delivered via Signal Phase and Timing (SPaT) messages. Thereby, vehicles approaching the traffic light can receive information on the current signal phase interval and time remaining to the next signal stage. Nearby vehicles receive the necessary information via a roadside unit (RSU) installed on or close to the traffic light and an on-board unit (OBU) mounted on a vehicle within a fixed communication distance. This distance might vary from 150 m up to 1000 m (see [20]). An optimal speed is advised to drivers individually depending on the current and future signal phasing and timing and the vehicle's position. The optimal target speed is calculated by taking into account the distance between the traffic signal and the approaching vehicle, and signal state upon arrival (whether green or red). Recommended speed advisories enable vehicles to pass through the downstream traffic light during a green interval, either without coming to a complete standstill or with minimal stopping at a traffic light.

Existing studies have provided promising outcomes for infrastructure-to-vehicle communication technologies regarding mobility and environmental benefits. Many of these studies are more focused on safety applications, fuel consumption and emission reduction estimations. These benefits are expected to be increased with higher V2I penetration rates [21], [22]. Two types of traffic signal timings; actuated- and fixed-time traffic lights were evaluated with the GLOSA system under a two-intersection road network through the Car2X platform of VISSIM. It is found that implementing GLOSA under fixed-timing is more effective than actuated signal timing [18]. Njobelo et al. [13] studied the queue discharge effect of the GLOSA approach with the Car2X interface of the VISSIM microscopic traffic simulator. An algorithm which considered queue dissipation time in the speed advisory calculation was developed. The results showed improvements in the number of stopped vehicles at a traffic light, stopping times and delays. Even though time spent in the queue decreased, a considerable number of vehicles' speed still declined to zero and led to queues forming [13]. Moreover, it is stated that vehicles equipped with speed advisory systems could indirectly improve the conventional vehicles fuel consumption, too. Similarly, the lower the traffic density, the less fuel is consumed because of minimised stops and acceleration and deceleration behaviours. The mean acceleration profiles of the V2I equipped vehicles were lower than those of conventional vehicles. However, the acceleration rate of equipped vehicles could sometimes result in exceeding the lower and upper acceleration values [23].

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The literature consists mainly of studies that simulate optimal speed advisory systems which are activated for the green phase of traffic signals. However, it is the red phase that causes conflicts and contributes to traffic-related problems. Moreover, rather than giving an optimal speed recommendation based on the speed itself, acceleration change is recommended. Nevertheless, drivers cannot comply with the acceleration suggestions easily. For this purpose, it is crucial to calculate and recommend an optimal speed to the vehicles arriving at a red status interval, too, which is more complicated compared to giving a target speed for a green interval arrival.

III. METHODOLOGY

Being relatively a new application makes the use of real-world testbed experiments to investigate GLOSA's impacts on mobility both difficult and costly. The available infrastructure also does not meet the required traffic conditions of the vehicular connectivity. Thus, microscopic traffic simulation modelling is used in this study.

A. Simulation Setup

An integrated simulation environment combining simulation software VISSIM with its external driver model is developed to examine the effectiveness of GLOSA systems at a microscopic level. VISSIM is capable of simulating and investigating each vehicle's behaviour individually in the network, and users can easily set up user-defined attributes to replicate any kind of vehicle's movements in the simulation. The Wiedemann's car following model, which is based on four driving states (i.e. free driving, approaching, following and braking), is used in the traffic modelling of VISSIM [24]. Behaviours of vehicles equipped with GLOSA and optimal speed advisory calculations are performed by the integrated simulation platform shown in Fig. 1. These can be done by using an application programming interface (API) of VISSIM called External Driver Model written in Visual Studio (C++).

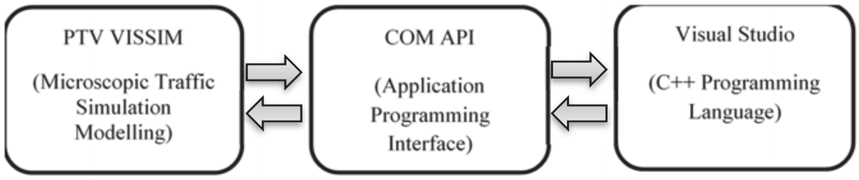

Fig. 1 The simulation environment

Simulating connected vehicles and vehicle-to-infrastructure communication necessitates modifications to the regular behaviour of the vehicles. Hence, a control algorithm is proposed so as to build up a connected vehicle environment with infrastructure-to-vehicle communication. In this regard, understanding GLOSA applications and CV behaviours are the first objectives for identifying what modifications need to be made to the default vehicle behaviours for the simulation.

B. Green Light Optimal Speed Advisory Algorithm Development

A control algorithm for GLOSA is developed via the external driver model of VISSIM. This algorithm facilitates communication between vehicles and infrastructure; in this case, traffic lights, for exchanging information. Henceforth, it gives optimal advisory speeds to vehicles approaching the relevant downstream traffic light to enable them to pass through during a green phase. The algorithm uses information from both the traffic light and connected vehicles to estimate an optimal speed. The main purpose of this algorithm is to provide advisory speeds for each vehicle continuously at every time step regarding the traffic light phase upon arrival (either green or red). Thus, such an algorithm can enhance the efficiency and performance of traffic flow at traffic signals in terms of minimising waiting times and average delays. Moreover, it can also have promising benefits for the environment as it alleviates excessive stop-and-go driving and speed variations for being the main reasons for fuel consumption and vehicular emissions.

First of all, input parameters need to be identified based on the purpose of the algorithm for building up to it effectively step by step. The input parameters of the algorithm involve the distance to the downstream traffic light, current speed of the vehicle, maximum allowed speed limit in the road network, and the signal phase and timing (SPaT) information. Then, these variables are used for estimations. The step-by-step explanation of the algorithm can be seen in Table I. In the algorithm, the compliance rate for following the advisory speed is assumed as being 100%; that is, all the GLOSA-equipped vehicles in the network follow their individual speed recommendations.

TABLE I
EXPLANATION OF GREEN LIGHT OPTIMAL SPEED ADVISORY ALGORITHM

1. Collecting data on vehicle speed, position and current traffic conditions.
2. Checking for the availability of any closest relevant traffic signal controller downstream.
3. If there is no traffic light, return to step 1, and repeat the algorithm process until detecting any relevant traffic light.
4. Else, if there is a traffic light ahead, then find the relevant and closest downstream traffic light and calculate vehicle's distance to traffic light, as well as collect data on signal phasing and timing; that is traffic signal phase (i.e. green or red) at the current moment.
5. Calculate the time required to arrive at the downstream traffic light and identify the phase at the arrival time.
6. If the phase of the traffic light is green upon arrival at the traffic light, then calculate an optimal speed for passing the light during the green phase.
7. If the advised speed is higher than the maximum legal speed limit for that road, then calculate another speed advisory with a delay to catch the next green phase. Otherwise, follow the given advisory speed in step 6.
8. Else, if the phase is red upon arrival, collect data on the remaining time to the next green.
9. Based on the time to green, calculate and advise another optimal speed with a delay to pass the light with a smooth driving behaviour.
10. If the advised speed is lower than the minimum speed limit, then speed up to the determined minimum speed limit (i.e. 50% of maximum speed).

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The control algorithm logic begins with identifying vehicles equipped with the GLOSA system entering into the communication range. In this study, the communication range is defined as 500 m. Then, the vehicle searches and detects if any relevant downstream traffic signal is available. If this criterion is not met, the process will be repeated until the vehicle detects any relevant downstream traffic light. Otherwise, communication begins by collecting data on the vehicle's current speed and position approaching the light. The position helps to identify the distance between the vehicle and the downstream traffic light. Thereby, depending on the approaching vehicle's distance to the next downstream traffic light, the arrival time is determined by taking the current speed and acceleration rate into consideration, too. The pre-determined signal phasing and timing, which involves the total cycle length, current traffic light status, predicted arrival cycle time, and starting and ending times of each phase, is instantaneously and regularly estimated and updated at every time step and sent back to the equipped vehicle. Arrival cycle time determines in which time interval the vehicle arrives at the traffic light and to what phase the arrival time corresponds.

If the approaching vehicle is able to arrive at the green phase at its current speed, then the vehicle is advised to maintain its current speed. However, if the recommended speed is higher than the maximum legal speed limit of the road, then the advisory assists the vehicle to make a decision on passing through the traffic light with a delay at the starting time of the next green. On the other hand, if the light is red upon arrival, an optimal speed advisory is recalculated with a delay for arriving during the next green phase interval. Therefore, the vehicle slows down its speed gradually to pass through the traffic light relatively without coming to a complete stop at the signalised control point. Nevertheless, if the advised speed becomes very low, then the vehicle will be recommended to comply with the minimum speed. A minimum speed limit, which is half of the maximum limit, is determined in order to avoid any conflicts in the traffic. After passing through all the relevant downstream traffic signals and leaving the communication distance range, the green light optimal speed advisory control algorithm terminates for that vehicle.

C. Simulation Test-Network

A simple microscopic traffic simulation network test bed is designed in VISSIM so as to implement the proposed control algorithm and examine its readiness for application. Furthermore, artificial data are used because of the unavailability of empirical signal and real connected vehicle traffic data.

The study network is a 1500 metre length straight road segment, which is composed of two opposite direction running lanes; right bound and left bound. There are two traffic lights per lane, which overall comprise the total traffic lights in the road network. The traffic lights are located every 500 metres on each lane. This distance also defines the communication range at 500 metres. As long as the equipped vehicle is within the 500 m range, the communication starts and continues with the first relevant downstream traffic light. Once the vehicle passes through the first traffic light, the communication terminates and starts again with the next upcoming one.

The lights are fixed-timed with a predefined cycle length of 72 seconds, and sequence of red, red/amber, green, and amber splits allocated 40 seconds, 2 seconds, 27 seconds and 3 seconds, respectively. Figs. 2-4 display a schematic illustration of the network. Fig. 2 is a screenshot of the designed VISSIM network. The composition of vehicles involves passenger vehicle only with a speed distribution interval of minimum 35 km/h and maximum 60 km/h. Traffic volume on the network is evaluated for two traffic volumes of 150 vehicles per hour (v/h) and 200 vehicles per hour (v/h) per lane.

Fig. 2 A preview of simulation test bed from VISSIM

Fig. 3 Simulation screenshot during a red phase interval in case of all conventional vehicles

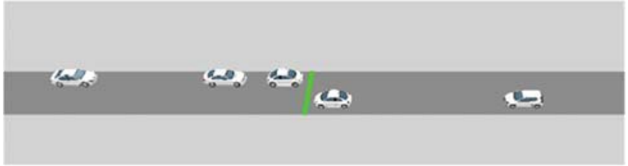

Fig. 4 Simulation screenshot during a green phase interval in case of all GLOSA-equipped vehicles

Two types of vehicles were allocated in the simulation test bed; conventional vehicles and GLOSA-equipped connected vehicles. Conventional vehicles were not supported by infrastructure-to-vehicle communication technologies, so that they randomly decide on a speed choice within the maximum and minimum boundaries of speed distribution. On the other hand, connected vehicles followed the recommended optimal speed advisories. Two different simulation scenarios were designed. The first scenario only involved conventional vehicles (i.e. 100% conventional vehicles, no connected vehicle). None of the vehicles in the simulation received any speed advisory, so that they followed any of the four states of Wiedemann car following model. For instance, vehicles either moved at a free flow or changed state when a certain threshold was reached depending on the traffic condition (i.e. approaching any vehicle or traffic light in front or stopping). Whereas, the second scenario only involved connected vehicles equipped with the GLOSA application (i.e. 100% GLOSA-equipped vehicles, no conventional vehicle). In this instance, all

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vehicles in the simulation network could receive information from the downstream traffic light. Therefore, they could travel with a smooth speed profile as they were recommended in advance at what speed they need to approach the traffic light. The first scenario was used as a base scenario for comparing results with the one of the GLOSA implementation.

IV. RESULTS AND DISCUSSIONS

Travel times and delay data were recorded in VISSIM by using data collection points located from the beginning of the network until the end for two different traffic volumes; 200 vehicles per hour and 150 vehicles per hour, respectively. The data for waiting times at traffic signals were also obtained from the trajectories of vehicles. The trajectory of every vehicle was recorded for 12 simulation runs with one speed number over 36000 seconds at the simulation speed of 10 seconds. Two different simulation scenarios were evaluated;

- 100% of conventional vehicles, no connected vehicles equipped with GLOSA in the network
- 100% of connected vehicles equipped with GLOSA, no conventional vehicles in the network

Measurement points in the network were located to collect data on every individual vehicle's delay. An average delay is calculated for each vehicle for a certain movement, in this study for example, for the entire right bound and left bound directions separately. Delay estimates the difference between the optimal travel time without any obstacles on the road and the real travel time. In this study, the average of all the individual delays was calculated and presented in Figs. 3 and 4 for traffic volumes of 150 vehicles per hour (v/h) and 200 vehicles per hour (v/h) per lane, respectively. When GLOSA was activated at 100% penetration rate for each direction under both 150 v/h and 200 v/h traffic volume conditions, Figs. 3 and 4 indicate a significant reduction in average delays by around 86.46% and 83.84%, respectively for the entire traffic network. Increasing the traffic density comparably influenced the impacts of GLOSA on delays; that is, the lower traffic density decreased delay events more compared to the higher density condition. In other words, higher traffic volume limits the driving styles due to increased vehicle interactions at traffic signals. Thus, the benefits of GLOSA increased under low traffic volume. These reductions in delays can also be explained by reallocating the delays on journey delays [18].

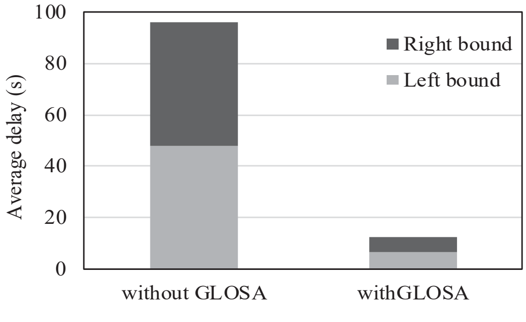

Fig. 5 Average delay of 2953 vehicles for 1500 m-long road involving two opposite directions under 150 v/h

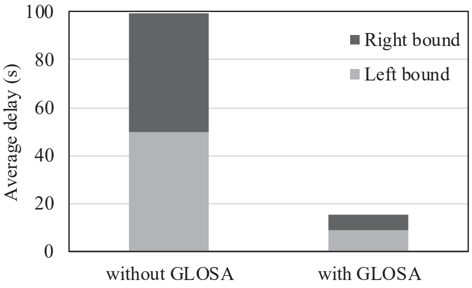

Fig. 6 Average delay of 3970 vehicles for 1500 m-long road involving two opposite directions under 200 v/h

In addition, speed profile analyses were done on randomly chosen vehicles per lane under two traffic volumes of 150 v/h and 200 v/h. The following figures illustrate four different vehicles' speed profiles with two cases of when GLOSA was not activated (i.e. conventional vehicles) and when GLOSA was activated (i.e. connected vehicles equipped with GLOSA. Figs. 7 and 8. show two random vehicles' speed profiles chosen from 150 v/h density. A vehicle with an identification number (ID) 119 was travelling towards right bound, and the other vehicle with ID 34 towards left bound on the experiment road scenario under 150 vehicles per hour per lane.

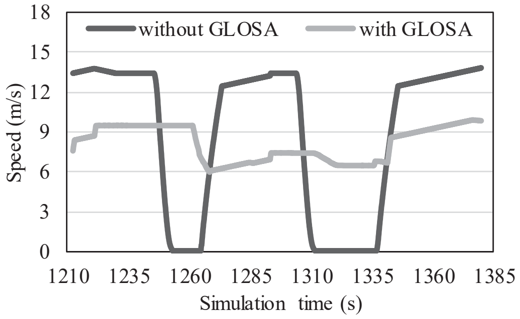

Fig. 7 Speed profile of vehicle ID 119 travelling under 150 v/h in the right bound direction

Fig. 7 presents the speed profile of a randomly chosen vehicle (among 2953 vehicles) with an identification number (ID) 119. This vehicle travelled on the right bound direction. The vehicle appeared in the scenario network at the simulation second of around 1650, which was positioned 500 m upstream of the first traffic light. The GLOSA-equipped vehicle (i.e. with GLOSA) approached to the first traffic light at a speed of above 9 m/s between the 1210 and 1385 simulation seconds. Even though this speed was slower than that of without GLOSA scenario, it enabled the equipped vehicle to reach the traffic light during the green phase. Therefore, unlike the case of without GLOSA, the speed of the connected vehicle equipped with GLOSA did not drop to zero between the simulation seconds of 1253 and 1264. Moreover, the change in the speed of the GLOSA-equipped vehicle was only around 4 m/s (10 m/s and 6 m/s), whereas this value was approximately 14 m/s (14 m/s and 0 m/s) for the conventional vehicle at the first traffic light. After the first traffic light, the connected vehicle approached the second traffic light with smooth speed. In the same way, the connected vehicle reached the second traffic light during the green phase where it did not even have to reduce its speed. However, the conventional vehicle became a complete standstill position again because of arriving during the red phase interval and had to wait for 26 seconds between simulation seconds of 1311 and 1337.

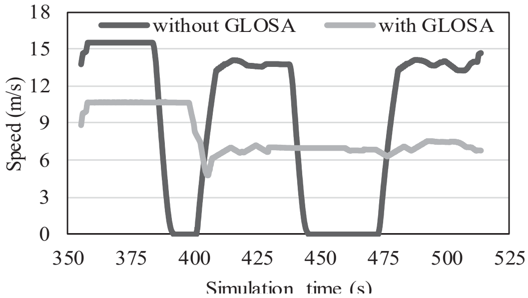

Fig. 8 Speed profile of vehicle ID 34 travelling under 150 v/h in the left bound direction

Similarly, another connected vehicle (ID 34) was randomly chosen from the opposite direction (left bound) from 150 v/h density per lane demonstrated a comparable outcome with the vehicle ID 119. Fig. 8 shows the speed distribution profile of the vehicle ID 34 versus simulation time in seconds. Similar to the previous case, this vehicle also approached to first traffic light approximately 4 m/s slower than the conventional vehicle. The conventional vehicle had to stop between simulation seconds of 391 and 400 for the first traffic light and 445 and 473 for the second, whereas the connected vehicle reduced its speed based on the speed recommendation (shown in Fig. 8) and passed through both the first and second traffic lights during the green phase by avoiding stopping.

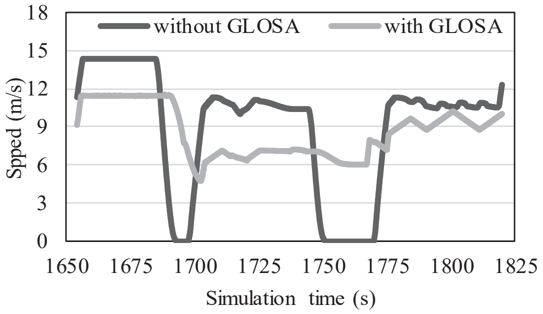

Fig. 9 Speed profile of vehicle ID 203 travelling at 200 v/h in the right bound direction

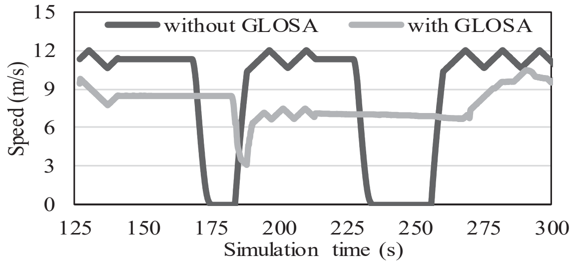

Fig. 10 Speed profile of vehicle ID 14 travelling under 200 v/h in the left bound direction

In addition, similar illustration and analysis were done for traffic density of 200 v/h. Two vehicles travelling on opposite lanes were chosen such as a vehicle with ID 203 (right bound) and 14 (left bound). Figs. 9 and 10 show the speed distribution of the vehicle with ID 203 and 14 versus simulation time. When GLOSA is activated, the equipped vehicles followed a smoother speed pattern compared with the speed profile of without GLOSA when conventional vehicles did not receive any recommended speed advisory message. Therefore, conventional vehicles had to come to a complete standstill position with their speeds dropped to 0 m/s at both traffic lights on right bound and left bound under 200 v/h per lane. However, speed advisory enabled the connected vehicles to avoid unnecessary stops at the traffic signals.

The conventional vehicles typically travel with relatively higher speeds as they cannot predict the appropriate speed limit to catch the downstream traffic light during a green phase. Further impact assessment of the GLOSA system can also be investigated through time-space diagrams, as shown in Figs. 11-14 for the same vehicles explained. The conditions held the same; that is, vehicles were randomly chosen from two opposite directions under 150 v/h and 200 v/h per lane traffic density. According to all presented time-space figures (from Figs. 11-14), it can be noted that the movements of conventional vehicles without GLOSA function were interrupted and came to a standstill at the traffic light. For example, the vehicle with an ID 119 stopped at the first traffic light between simulation second of 1253 and 1264 for 11 seconds and at the second traffic light between 1311 and 1337 for 26 seconds.

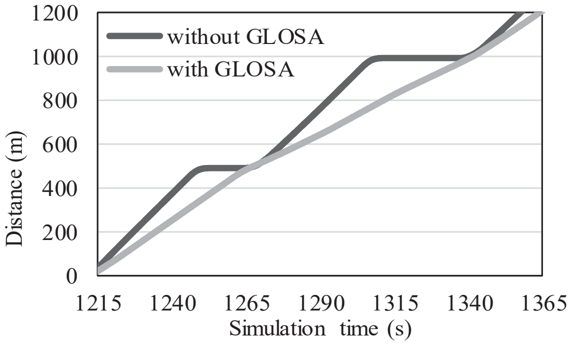

Fig. 11 Time-space diagram of vehicle ID 119 travelling right bound under 150 v/h

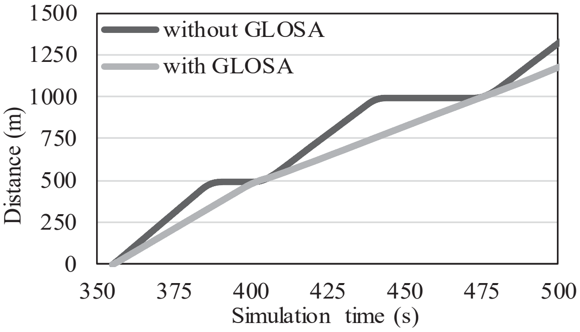

Fig. 12 Time-space diagram of vehicle ID 34 travelling left bound under 150 v/h

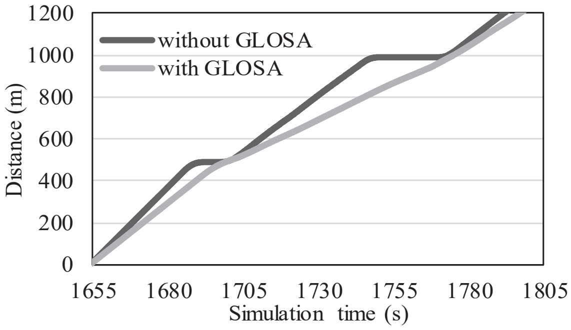

Fig. 13 Time-space diagram of vehicle ID 203 travelling on right bound under 200 v/h

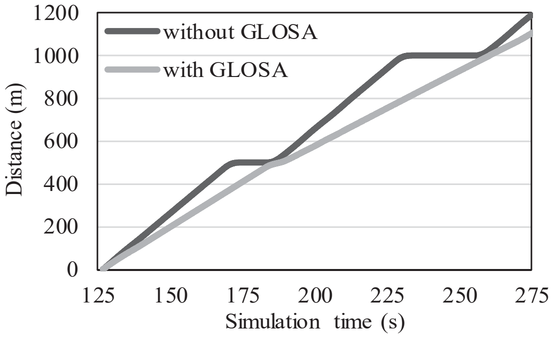

Fig. 14 Time-space diagram of vehicle ID 14 travelling on left bound under 200 v/h

Waiting times were reduced up to 11 seconds for the first traffic light and 28 seconds for the second based on the reference vehicles illustrated in this study area. Because GLOSA-equipped vehicles were recommended by an individually calculated green light optimal speed advisory system, they could adapt their speed correspondingly and traverse the test bed road network smoothly. Therefore, the waiting time at traffic lights was either avoided or minimised by an improved driving behaviour controlled by the developed algorithm. The results are promising and in agreement with the previous literature. To illustrate, Eckhoff et al. (2013) [25] developed a large-scale simulation-based study. The effects of informing drivers in advance by GLOSA were examined from the environmental point of view. Besides, number of stops and waiting times at traffic lights were studied. The results stated that under lower traffic density conditions, number of stops and waiting times were improved by up to 6% and 17%, respectively, with an approximately 12% improvement in fuel consumption and emission reduction [25]. In a like manner, the LOSA application was simulated with a single direction composed of two traffic signals. Stop time behind traffic lights reduced around 80% and fuel consumption decreased up to 7% [22].

V. CONCLUSIONS AND FUTURE WORK

In this study, simulation-based green light optimal speed advisory system is implemented by using a control algorithm developed by integrating VISSIM with C++ via COM interface. The algorithm was examined on a 1500 m length straight road segment with two opposite directions under two cases of 100% penetration rate of equipped vehicles and 100% penetration rate of conventional vehicles at 150 and 200 vehicles per hour traffic conditions. The results show that receiving information on the accurate phase interval of traffic signals beforehand is effective in improving traffic performance regarding average delays and waiting times. When green light optimal speed advisory is activated at 100% penetration rate, the average delay of the entire road segment decreased significantly by around 86.46% and 83.84% under traffic volumes of 150 v/h and 200 v/h, respectively. Similarly, waiting times of vehicles at traffic signals also decreased up to 28 seconds with the green light optimal speed advisory system.

In the future, the proposed algorithm needs to be tested on a real-world road segment with real-world empirical traffic and signal data under traffic simulation platform. Depending on the specified network, the control algorithm can be improved and adapted with the necessary parameter modifications on vehicle behaviours. This can also be analysed under different penetration and driver compliance rates. In other words, under a mixed traffic environment both conventional and connected vehicles can be simulated together. Driver compliances can also be considered at various rates to investigate whether or not following a given speed advisory has a considerable impact on the traffic efficiency. Furthermore, the vehicles' trajectories data obtained from the simulation can be further used to estimate the impacts of green light optimal speed advisory systems on vehicular emissions.

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