27th ITS World Congress, Hamburg, Germany, 11-15 October 2021

Paper ID #210

Dynamic adapted green light optimal speed advisory for buses considering waiting time at the closest bus stop to the intersection

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Abstract

A large amount of present green light optimal speed advisory (GLOSA) systems are for private vehicles. However, as one of nonnegligible transportation modes, public transportation is worth more attention. Some GLOSAs just provide several driving models with fixed speeds and accelerations which is extremely difficult for human-drivers to obey strictly and adapt dynamically. Therefore, this paper proposes a GLOSA for buses (GLOSA-B) considering the waiting time at the closest bus stop to the target intersection. By means of V2X communication based on ITS-G5 (IEEE 802.11p), this GLOSA-B could provide a range of recommended speeds and update calculation every second. To validate the proposed algorithm, 20 groups of GLOSA and non-GLOSA buses are simulated. The results indicate that this GLOSA-B could avoid unnecessary stops significantly. Compared with non-GLOSA buses, the GLOSA buses save waiting time at the target intersection by 98.95%.

Keywords:

V2X, mobility management, GLOSA, public transportation

Introduction

Along with the development of intelligent transport systems, Vehicle-to-X (V2X) communication is becoming a kind of common technology in Cooperative Intelligent Transport Systems (C-ITSs) which is constructed based on Vehicle AdHoc NETworks (VANETs) [1]. Normally, the messages in C-ITSs are broadcasted in forms of CAM (Cooperative Awareness Message), DENM (Decentralized Environmental Notification Message), MAP (Map Data Message), SPAT (Signal Phase and Timing Message), SREM (Signal Request Extended Message), SSEM (Signal Request Status Extended Message) and so on [2, 3]. As an important application of V2X communication, Green Light Optimal Speed Advisory (GLOSA) systems can firstly acquire information such as current position and signal plans via broadcasts of RSUs (Road Side Units). Then some data of vehicles will be processed, such as current velocity, distance to the intersection, and residue time to the upcoming green signal. Finally, a speed recommendation can be generated to advise the driver an optimal crossing speed to go through the intersection without any stop. It has been proven that GLOSA plays a crucial role in the reduction of CO_2 and fuel consumption [4, 5, 6], by means of reducing the travel time and waiting time at intersections [7]. According to the algorithms, GLOSA systems can be categorized into single-segment and multi-segment systems [8].

For single-segment approaches, Suramardhana et al. proposed six mobility models with different levels of accelerations and decelerations for a driver-centric GLOSA [9]. The examination experiments of this GLOSA system proved that the waiting time could be decreased by 23.9% on average [9]. Considering platoon-cases, Stebbins et al. raised up a GLOSA algorithm integrated with trajectory functions, which could be further used for autonomous driving [10]. After evaluation, applied in this situation, the GLOSA system could save time by 30~50% and reduce fuel consumption by 15~20% [10]. From an innovative point of view, Suzuki et al. designed a new indication of recommended speed by presenting GO and NOGO rectangular bars on the road by means of head-up display (HUD) [11]. This GLOSA system was realized by visual technologies, focused on available distances in the corresponding signal phases, which can help drivers keep appropriate speeds in an easier way. It has a high potential to reduce CO_2 emissions and improve fuel efficiency by avoiding inappropriate decelerations, however, the travel time would not change significantly [11].

From an overall view of a whole route, which is normally divided into several segments by traffic signals in series, Seredynski et al. put forward a multi-segment GLOSA to minimize the total fuel consumption or travel time [12]. Compared with single-segment GLOSA in off-peak hours, this innovative multi-segment method was proved to be a better solution with significant advantages [12]. Considering different energy consumption models of electric vehicles, Simchon et al. developed a dynamic GLOSA system for e-vehicles, which could be implemented for real-time cases [13]. Taking into account the trade-off between the travel time and energy consumption, an optimal speed planning could be generated by the optimization calculation model. By means of simulation, this dynamic GLOSA for e-vehicles could result in a reduction of energy consumption by 50% and save more than 6% of the travel time[13]. Combined with autonomous driving and multi-segment algorithms, a novel R-GLOSA system was put forward by Nguyen et al., applying the communication between RSUs [14]. Compared with traditional single-segment and multi-segment approaches, the proposed R-GLOSA was proved to outperform in terms of travel time and fuel efficiency [14].

As one of the main modes of transportation, public transport attracts a lot of attention. Especially for buses where routes are settled and schedules are strict, there is a high demand for a GLOSA system to improve fuel efficiency and reduce waiting time at intersections. Generally, in order to maintain service regularity, holding and stop skipping are adopted by operators [15]. Combining a holding criterion and speed advisory, a kind of hybrid controller for buses was raised by Laskaris et al. [16], namely a combination of GLOSA and GLODTA (Green Light Optimal Dwell Time Advisory). But the limitation was that all signal programs have to be fixed time. Later, the authors further enhanced the bus holding control by means of the communication of C-ITS [17]. It is the first research to study the combination of GLODTA, GLOSA, and TSP (Transit Signal Priority) at a line level [17]. The results of the evaluation and simulation of the selected bus line in Luxembourg presented that this controller could cut down significantly the requests for TSP to keep regularity, and meanwhile, avoid influences on other traffic flows [17]. Colombaroni et al. [18] designed a GLOSA system taking into account the TSP of buses, then simulated this model-based method for a tram line in Rome. After simulations of different bus priority rules, this GLOSA system was proved to be able to not only reduce the delay of bus riders, but also improve the whole efficiency of the total traffic [18].

In the previous research, GLOSA systems were designed for private vehicles, neglecting the dwell time of buses at stops. The typical driver-centric GLOSA usually adopts several concrete accelerations or decelerations to represent diverse driving modes, which could be different from the practical cases for all vehicles [9]. In many cases, once the speed recommendation is provided, the calculation might not be adjusted in real-time according to the actual velocity [19, 20]. Generally, in most conventional GLOSA systems, an optimal passing speed is only provided, which is difficult for drivers to maintain strictly and exactly [19].

As a result of the limitations of GLOSA for buses (GLOSA-Bs) in present research, this paper will design a novel GLOSA-B, considering both the waiting time at bus stops and optimal speed to pass through the signaled intersections. Via communication with the C-ITS in real time, this novel GLOSA-B will firstly tell the bus driver an appropriate waiting time at the stop to close the door and departure. Then when the bus leaves the stop, a recommended range of driving speed will be provided instead of a concrete index, in order to help the driver manage the speed more flexibly and easily. This proposed GLOSA-B will update the optimal range of speed every second, which could therefore, simplify largely the algorithm of GLOSA with a neglect of actual acceleration or deceleration. Because if the diver is aware of the difference between the practical speed and optimal range, then the driver will adapt driving behavior flexibly instead of obeying a defined acceleration. Different from typical GLOSA-Bs, this dynamic adapted GLOSA-B will focus only on the closest stop to the intersection rather than at a line level, in order to reduce the cost of communication in the whole traffic network.

The rest of this paper is structured as follows. Section 2 introduces the applied communication mechanism for V2I in the use case. Section 3 explains mainly how the proposed GLOSA-B algorithm built and formulated. Furthermore, in order to evaluate the algorithm, a simulation for both GLOSA buses and non-GLOSA buses is proceeded in Section 4. Section 5 summarizes the main conclusions.

V2I communication in the use case

There are many wireless technologies that could be used to realize the communication between several vehicles as well as between vehicles and infrastructure. V2X via IEEE 802.11p has become mature, new specification releases are frequently tested and, maybe most importantly, there are several 11p ready devices on the market that can be utilized in custom use cases. This technology and all corresponding specifications are also called ITS-G5.

One key advantage of ITS-G5 is the ad-hoc communication that doesn’t need a network like normal WiFi or cellular networks like 4G does. The technology of 5G (“New Radio”) has already been rolled out for end consumers. But its use in ITS is still a research topic and the ad-hoc communication feature still needs to be specified and thoroughly tested.

The basis of ITS-G5 is WiFi plus many adjustments. The top protocol layer defines several message formats specifically for the use in ITS use cases, like CAM, DENM, MAP, SPAT, SREM, SSEM. In this work, standardized messages MAPEM and SPATEM (European versions of MAP and SPAT) are adopted for the GLOSA-B. Two RSUs have been installed in the test field to send SPATEM: one is for the precise traffic light status (current color), another one is for the precise forecast of the color switching time. The OBU is responsible for merging these data.

The communication between the RSUs and the bus is done via V2X / ITS-G5, while the interprocess communication on the OBU is realized with an MQTT message broker. In this way, the relevant data can be extracted from V2X messages and is published via a JSON string on the OBU and a local Ethernet/WiFi network. The GLOSA-B algorithm subscribes as a client to these topics. In addition, displays or a laptop for debugging can subscribe as further clients.

The communication mechanism of the dynamic adapted GLOSA-B in this paper is structured in Fig. 1. As presented in the architecture, the field device is constructed by the TLC (Traffic Light Controller) connecting with a RSU, which is called RSU-TLC in this work. The TLC will firstly send related application values with some standard TLC process data to the traffic center, then the traffic center will transfer the required data to the public transport strategy computer as inputs for further process. After computing, a forecast SPAT message will be generated and transferred to a RSU auxiliary. Finally, the current SPAT message will be sent by RSU-TLC, while the forecast SPAT message will be broadcasted by the RSU auxiliary simultaneously. An OBU (On-Board Unit) will be implemented on a bus to receive the current & forecast SPAT, and MAP messages of target intersections. After merging and processing, the OBU will send required data to the GLOSA-B system.

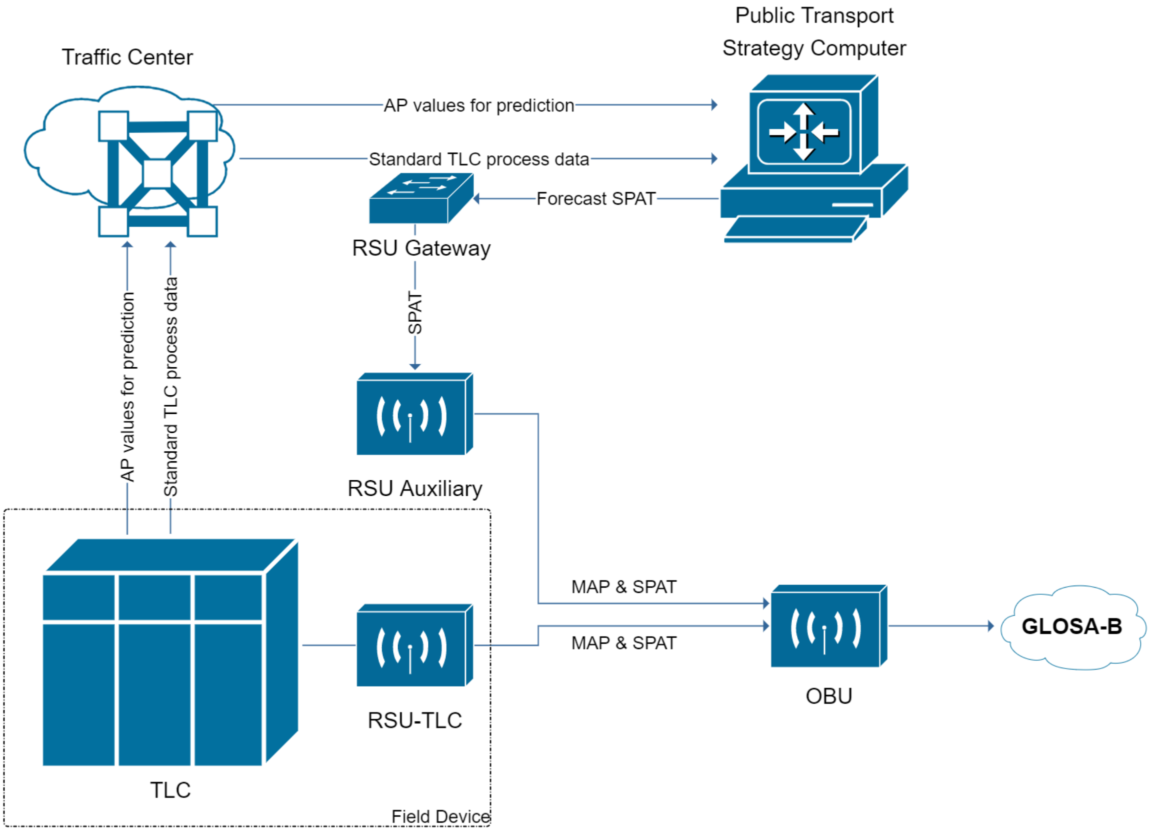


Figure 1 - Communication system architecture in ITS

GLOSA-B algorithm

As described in Fig. 2, via the communication with the RSUs, messages such as MAP, SPAT, and forecast SPAT could be obtained as inputs to the GLOSA-B application. Additionally, the bus route information is assumed to be available in OBUs.

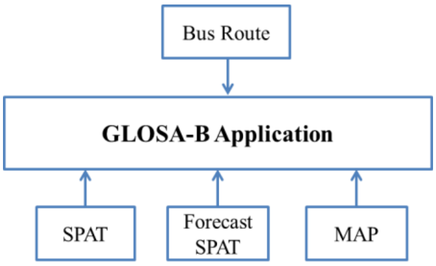


Figure 2 - Inputs to GLOSA-B application

Communication data process

The communication starts with obtaining MAP messages. Each MAP message describes the position of different lanes for different intersections. For every second, the algorithm checks which lane is the closest to the current GNSS (Global Navigation Satellite System) position (assuming it to be always available). Once the current lane is identified, the coordinate of the corresponding intersection will be found out. The signal group, connected to the lane is also retrieved. With this information, the event state corresponding to this signal group and its end times, both minimum and maximum, are retrieved from the SPAT message. When the SPAT message gives the timings of the current signal, the forecast SPAT will provide information about the overall signal cycle of the signal group.

Algorithm description

The application starts as the bus approaches a bus stop closest to the target intersection and runs as long as the bus hasn't crossed the intersection. Despite performing the same computations, the algorithm differs according to the positions of the bus. It depends on whether the bus is at the stop or moving from the bus stop to the intersection.

Algorithm 1 GLOSA-B algorithm

```
Find the relevant intersection $int$
Compute distance to $int$, $distToInt$
Find the relevant signal group $sg$
Find the current signal in $sg$, $s$
Set $timeToGreen$ as the time remaining for the next GREEN in $sg$
Compute $desiredSpeed$
Set $currSpeed$ as the current speed (from GNSS or Vmin)
Refine $desiredSpeed$ (refer Algorithm 2)
if $currSpeed$ is in range of $desiredSpeed$ then
    Proceed
else if $currSpeed < desiredSpeed$ then
    Accelerate
else if $currSpeed > desiredSpeed$ then
    Decelerate
```

Since the relevant intersection and signal group are obtained from the MAP message, distance from the current position to the intersection is computed by means of the bus route data. As described in Algorithm 1, the remaining time for the next GREEN is computed from the signal cycles given by forecast SPAT. The current speed is obtained from the GNSS message if the bus is moving. Otherwise, it is assumed to be the minimum permissible speed if the bus is at the bus stop. As presented by (1) the desired speed is computed considering the distance to intersection and the time remaining for the next GREEN, where the time needed to close the doors for the passengers to board and deboard is assumed to be 10s.

$$\text{desired speed} = \frac{\text{distance to intersection}}{\text{time remaining for GREEN - time to close doors}} \tag{1}$$

However, there could be cases when the desired speed is not in the permissible range and providing this speed advisory shall prove infeasible considering the real-world application of GLOSA. This demands a second phase of computation, when the desired speed is further refined and brought under the permissible bounds. As defined in Fig. 3, *Vmin* and *Vmax* are the minimum and maximum permissible speeds, *V1* and *V2* are the minimum and maximum limit of the computed desired speed. If the desired speed is not within the range of (*Vmin*, *Vmax*), the non-adhering bound(s) of the desired speed is capped to the permissible bound(s), which is shown in Fig. 3 (b) ~ (d). If the desired speed is much lower than *Vmin*, it implies the bus has to wait at the bus stop for a period of time, at least until *V2* is greater than *Vmin*. Similarly, when the desired speed is much greater than *Vmax*, the algorithm will prompt the driver to wait at the bus stop as long as *V1* is less than *Vmax*. In both cases, shown in Fig. 3 (e) and (f), the desired speed is re-computed based on the next possible signal cycle. These steps are detailed in Algorithm 2, where lines 2~4 and 10~12 apply only when the bus is at the bus stop. When the bus is moving from the bus stop to the intersection, the speed computation will not include waiting periods.

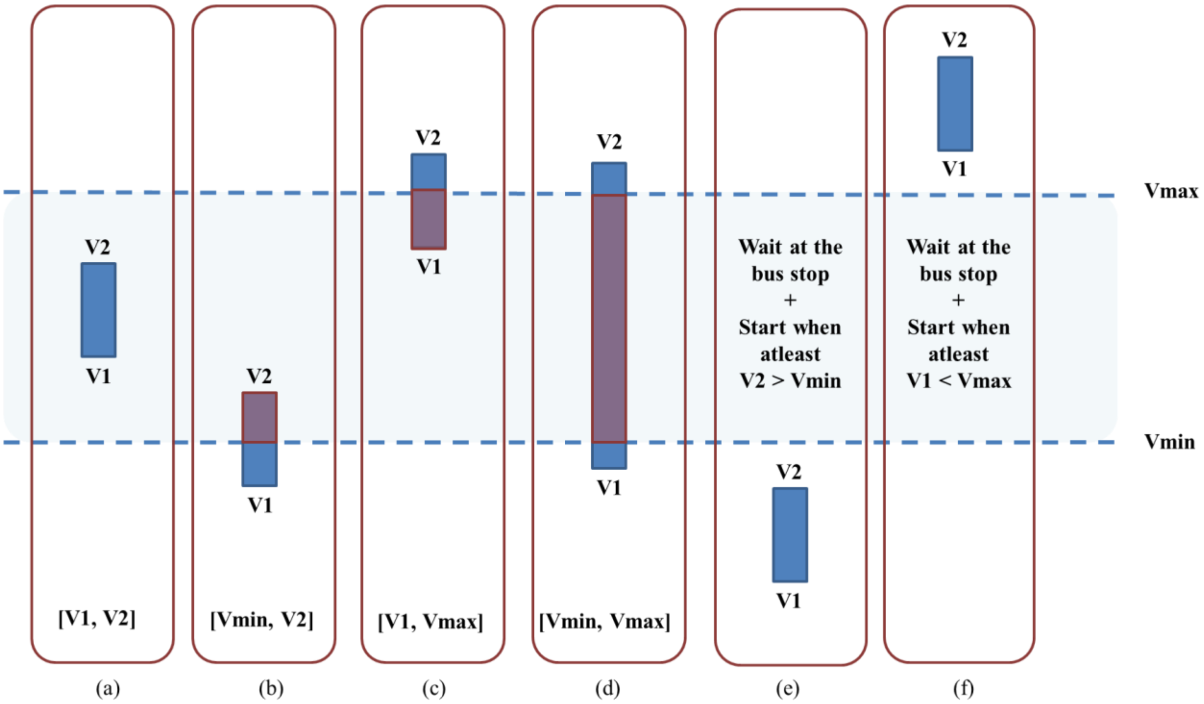


Figure 3 - Different scenarios of computing and refining desired speed ranges. Desired speed is within the permissible speed range in (a). Capping the speed at *Vmin* and/or *Vmax* is necessary for (b) ~ (d), the shaded region is the re-computed desired speed. Waiting at the bus stop and checking the next cycle of the signal is necessary for (e) and (f).

```
Algorithm 2 Refine desiredSpeed
Require: desiredSpeed (V1, V2) is not in range (Vmin, Vmax)
if $V1$ <Vmin then
    if $V2$ <Vmin then
        Check for the next GREEN in $sg$
        Wait at the bus stop, at-least until V2 > Vmin
    else if $V2$ is in range (Vmin, Vmax) then
        Set $desiredSpeed$ as (Vmin, V2)
    else
        Set $desiredSpeed$ as (Vmin, Vmax)
if $V2$ >Vmax then
    if $V1$ >Vmax then
        Check for the next GREEN in $sg$
        Wait at the bus stop, at-least until V1 < Vmax
    else if $V1$ is in range (Vmin, Vmax) then
        Set $desiredSpeed$ as (V1, Vmax)
    else
        Set $desiredSpeed$ as (Vmin, Vmax)
```

Once the desired speed is refined, the speed advisory can be provided in terms of

a. ‘Proceed’ if the current speed is in the range of desired speed.
b. ‘Accelerate’ if the current speed is less than the desired speed.
c. ‘Decelerate’ if the current speed is greater than the desired speed.

For Case b and c, the bus driver should also be notified of the desired speed range and the current speed, with which the bus can go through the intersection in GREEN time.

Simulation and results validation

To validate the proposed GLOSA-B algorithm, a simulation setup was developed and experimented with

20 different runs of GLOSA and non-GLOSA buses through the route of Bus 26 in Hamburg, the route with coordinate-points is shown in Fig. 4. The coordinate of the bus stop is (53.6025272, 10.1277754) and the intersection is located at (53.5998134, 10.1298669). The distance from the starting point of the trip (53.6034413, 10.1271376) to the intersection is approximately 432 m and the distance from the bus stop to the intersection is about 352 m.

Figure 4- The target intersection in Hamburg with routes of Bus 26

Simulation establishment

Considering the actual case and German traffic rules, the permissible speeds for the buses are set to be *Vmin* = 5 m/s and *Vmax* = 13.89 m/s. As depicted by Fig. 5, the concerned signal group 'K1' at the intersection is assumed for the simulation to be cyclic in the received SPAT messages, where GREEN lasts for the first 55 seconds, then YELLOW for 3 seconds, followed by 32 seconds of RED. One signal cycle lasts for 90 seconds and it repeats in the same order throughout the simulation. The starting times for simulation were selected randomly and uniformly in the whole signal program.

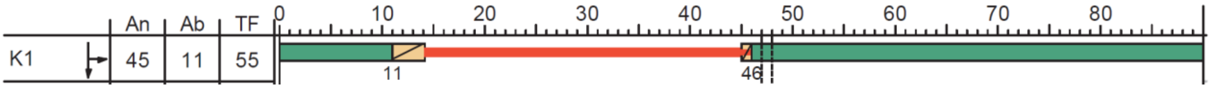
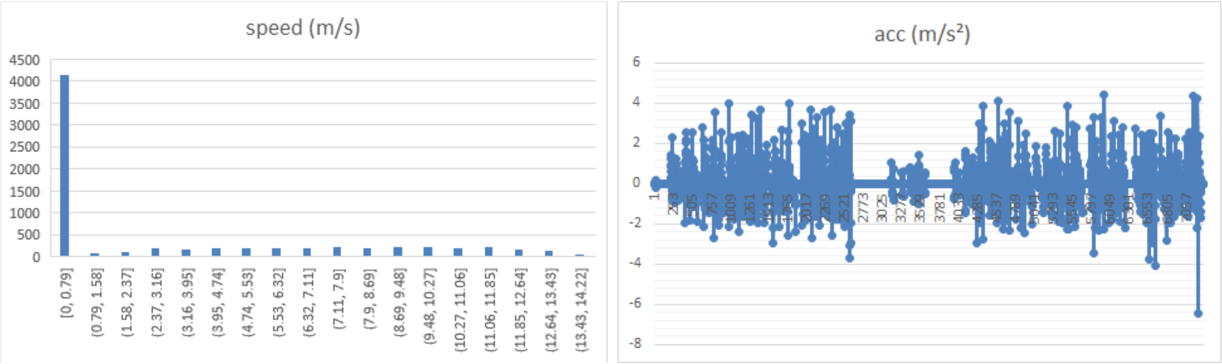


Figure 5 - Signal plan for the intersection

It is also assumed that the necessary inputs to the GLOSA-B algorithm are fed every second of the simulation without fail. This includes MAP, SPAT, forecast SPAT and GNSS from the RSUs and bus route information in the OBU.

For simulation, a GPS logger was implemented on a vehicle following the Bus 26 to record the speeds, which are shown in Fig. 6 (a). Excluding the most values below 0.79 m/s, a speed of 7.5 m/s is selected as a reachable medium speed for simulation with a high occurrence rate. Then the acceleration data is generated in Fig. 6 (b). After analysis, a group of reachable and acceptable parameters are selected for GLOSA and non-GLOSA buses, which are presented in Table 1.



(a) (b)

Figure 6 - Speed record and acceleration data of Bus 26 running in Hamburg

Table 1 - Types of simulated buses

Type of bus	Description
GLOSA bus	adjusts to the speed advisory gradual acceleration $< 3.5\ m/s^2$, maximum acceleration of $3.5\ m/s^2$ gradual deceleration $< 2.5\ m/s^2$, maximum deceleration of $2.5\ m/s^2$
Non-GLOSA bus	does not follow the speed advisory travels with a maximum velocity of 7.5 m/s constant acceleration at $3.5\ m/s^2$, constant deceleration at $2.5\ m/s^2$

Results analysis

It was observed, as shown in Fig. 7, the GLOSA buses took an average of 43 seconds to reach the intersection while non-GLOSA buses took around 54 seconds on average. There is no surprise that the non-GLOSA buses had to wait at the intersection for around 9.5 seconds on average for the GREEN signal. This amounts to about 10.6% of the total signal cycle time. As shown in Fig. 8, only 2 out of 20 GLOSA buses reached the intersection with 1 second remaining for GREEN, all the other buses reached the intersection when the signal had already been GREEN. This tiny error could be eliminated simply by narrowing down the recommended speed range.

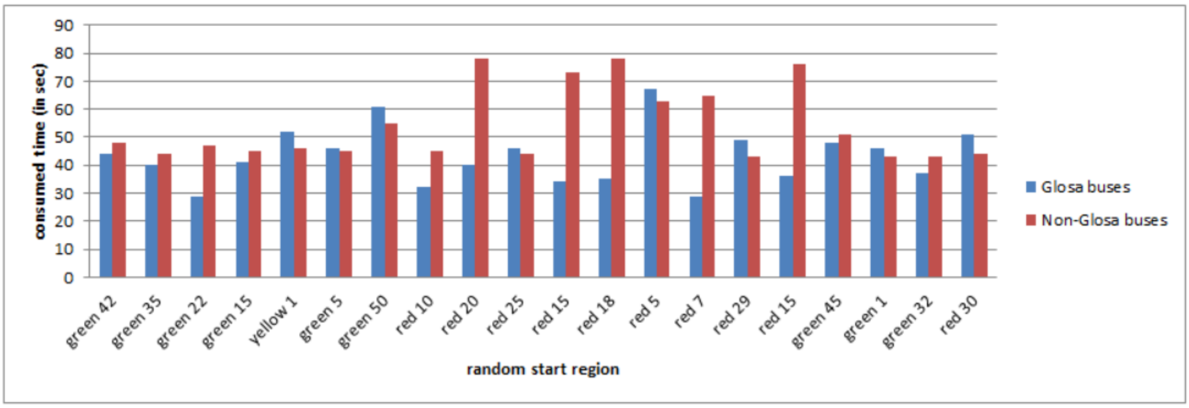


Figure 7 - Time consumed by buses for different start regions

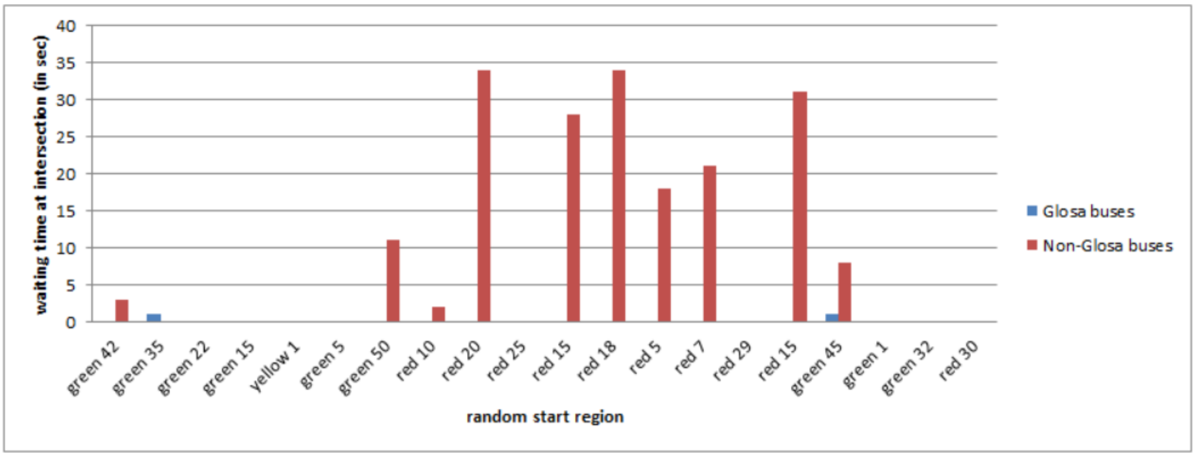


Figure 8 - Waiting time of buses at the intersection for different start regions

Conclusion

Based on existing GLOSA systems for vehicles, this paper presents a GLOSA-B algorithm for buses, considering the waiting time at the closest stop to the intersection. By means of communication with C-ITS, GLOSA-B can obtain the SPAT, forecast SPAT, MAP, and further route information as inputs.

According to the starting and ending time of GREEN or next GREENs, the algorithm will calculate possible time to close the doors, and appropriate speed range to guarantee the bus goes through the intersection without stopping. After simulation and comparison of GLOSA and non-GLOSA buses, the results show that, only 2 out of 20 GLOSA buses reached the intersection 1 second earlier than the start of the GREEN signal. With the assistance of GLOSA-B, it saves 98.95% waiting time at the intersection, which could be adapted to 100% by only adjusting the recommended speed range slightly.

The proposed GLOSA-B in this paper was proved to be able to not only remind the bus driver of closing time of doors at the closest bus stop to the intersection, but also help avoid unnecessary stops at the traffic signal at a large level. Therefore, it is obvious that GLOSA-B can reduce the energy consumption successfully. Compared with non-GLOSA buses, the travel time of GLOSA buses from the bus stop to the intersection was also reduced on average. For further validation, the GLOSA-B system is expected to be implemented on real buses and put into use in practical conditions, considering actual random cases like traffic jams. However, the influence of GLOSA-B on the rest traffic (e. g. private cars) is still not clear, a further research needs to be proceeded to adapt the GLOSA-B for all traffic flows. But there is a fact that due to the development of IoT technologies in ITS, GLOSA will be more widely applicated for all traffic participants (i.e. private cars, pedestrians, cyclists etc.). Therefore, in this case, the adverse impact of GLOSA-B on the rest traffic will be eliminated in the future transportation network.

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