CASPT 2018 Full Paper

Towards Optimised Deployment of Electric Bus Systems using Cooperative ITS

Georgios Laskaris · Marcin Seredynski · Francesco Viti

Abstract In this paper we analyse the impact of using cooperative intelligent transportation systems (C-ITS) to manage electrical bus systems. A simulation-based study is presented where three control strategies are used to regulate the operations of a line, namely bus holding, Green Light Optimal Dwell Time Adaptation (GLODTA) and Transit Signal Priority (TSP). The results show, using a realistic scenario of a major line in Luxembourg City, that buses are efficiently operated without necessarily providing additional priority to public transport, hence without negatively affecting the capacity of the private vehicles system. Benefits in terms of headway regulations, energy consumption and travel time variance reductions are quantified.

Keywords: Public transport · Cooperative ITS · e-buses · Driver Assistance Systems

1 Introduction

Sustainable urban development motivates investments in environmental-friendly and user-centred Public Transport (PT) services. Recent trends towards next generation PT systems show the development of greener vehicles such as battery electric/hybrid buses (e-buses), which are introduced to reduce the emission of pollutants, especially in urban environments (thanks to the implementation of, for instance, zero-emission zones), and the noise caused by traditional combustion engines. Apart from engine technology advancements, increased penetration of e-buses is also favoured by the introduction of new solutions at the level of charging infrastructures (opportunity or on-route charging, flash charging), which allow extending the operational range of electric vehicles.

Georgios Laskaris, Francesco Viti (corresponding author)
University of Luxembourg, Esch-sur-Alzette, Luxembourg
Email: {georgis.laskaris; francesco.viti}@uni.lu

Marcin Seredynski
Volvo E-Bus Competence Center, Livange, Luxembourg
Email: marcin.seredynski@consultant.volvo.com

A second trend is observed on bus operators seeking higher service quality beyond conventional performance measures such as service regularity and/or punctuality, for instance through increased ride comfort and reduced emissions and energy consumption via mitigation of stop-and-go driving patterns. These additional features are possible thanks especially to the introduction of sensors allowing real data information retrieval (automatic vehicle location, automatic passenger counts, etc.) and communication between all actors involved in the bus eco-system (vehicle-to-vehicle and vehicle-to-infrastructure communication). These technologies, which define the so-called Cooperative Intelligent Transportation System (C-ITS), offer great potential to improve the overall system performance, and to increase the level of driving control and automation. In particular, more conventional bus control systems (holding, stop skipping, etc.) and Transit Signal Priority (TSP) can be extended and improved thanks to information on e.g. signal times and phases of traffic lights, hence reducing the number of unneeded stops or signal timing changes. C-ITS has also great potential in reducing bus operating costs related to energy consumption and equipment wear and tear during bus operations (Seredynski and Viti, 2016).

These trends, however, bring new challenges. The first one is due to different operational characteristics and constraints characterising e-buses, e.g. they need to periodically recharge batteries at charging stations placed in terminals and (optionally) in bus stops. Despite fast technological advancements are showing that range extension of e-buses is growing significantly, it is still hard to imagine fully electric buses to operate the whole day without being recharged at some point of the day. This brings additional complexity into PT operations and its costs. The second challenge is to find measures able to provide comfort- and cost-related benefits without negatively impacting the general traffic performance. Relying solely on strategies such as TSP, which prioritises buses at signalised intersections penalising the other traffic streams, might cause congestion effects that could backfire on the PT system itself via blocking back phenomena.

In this paper, we demonstrate how these challenges can be effectively addressed by the emerging Cooperative ITS solutions. A novel framework addressing the problem via combination of cooperation and multi-objective optimisation is introduced. In particular, we extend two C-ITS-based driver assistance systems, namely the Green Light Optimal Speed Adaptation (GLOSA) and Green Light Optimal Dwell Time Adaptation (GLODTA), which adapt driving speeds and holding times, respectively, to avoid buses to arrive at nearby traffic lights during the red phase, hence reducing the number of stops at intersections. We investigate how the use of such C-ITS based solutions contribute to minimise total energy consumption. We also show that, by adopting these solutions, we reduce the need to resort to transit signal priority, hence in turn we reduce the negative impacts on private traffic.

The paper is structured as follows. The next section provides a review of the relevant literature. Then, Section 3 describes the whole methodology. Section 4 presents a realistic case study on an electrified urban line and then compares different strategies both in terms of operational efficiency and in terms of energy consumption. Finally, Section 5 provides the main conclusions and recommendations for future research.

2 Literature Review

PT systems consisting of e-buses reduce emissions, energy use, noise as well as offer smoother rides (Lajunen, 2014). Currently, e-bus systems are moving from pilot projects to small-scale deployments with single line/operator and with very few charging stations. The potentials and technical needs of large-scale e-bus systems have been recently under investigation by, for instance, the EU's Zero Emission Urban Bus System project (ZeEUS, 2018). Peak demand charges (based on the maximum amount of electrical power drawn from a grid within certain period) are a major barrier to e-bus deployment (Gallo et al., 2014). As opportunity charging provides the technical feasibility for the deployment of fully electrified lines, it comes with high costs for the line operators, and, in future large deployment scenarios, may create issues for the electrical grid, it is important to find measures to reduce the energy consumption during operations to reduce the need for daily charging operations.

Therefore, the charging requirements create a strong link between infrastructure planning and bus operations (Rogge et al., 2015). Currently, approaches for optimal recharging of e-bus systems are based on design and economical principles and do not consider in detail the actual energy consumption at the operational level (e.g. Xylia et al., 2017). The existing research efforts currently focus on developing a proper system design such as deploying strategic locations of charging stations (Fusco et al., 2012; Pternea et al., 2015). At operational levels, energy efficiency is currently addressed via energy management strategies for the engine (Peng et al., 2017), and regenerative breaking technologies (Li et al., 2016).

Additional gains in terms of both operational efficiency and reduced energy consumption can be obtained through prioritising PT systems at intersection through Transit Signal Priority (TSP) (Hu et al, 2015). Currently, in the literature, TSP, together with holding control strategies (Ibarra-Rojas et al., 2015; Laskaris et al., 2016) have been designed to only support the simple punctuality objectives or aim at regulating headways in frequency-based bus systems. TSP strategies can be seen as cost-efficient, since they overall reduce the number of stops at signals, hence avoiding additional stop-and-go operations. On the other hand, such control measures may have some negative impact on the general performance of the whole urban transport system: excessive use of TSP may reduce the capacity of competing traffic streams. Holding strategies have also some limitation as, by delaying buses at stops, they may

increase the total trip times, increase passenger on-board and waiting times, and force line operators to increase the fleet size in order to guarantee a certain service level.

Connected vehicle technology can also contribute to reduce the energy consumption, and in the same time improve operational efficiency of bus systems. In particular, the communication of Signal Phase and Timing (SPaT) information obtained from traffic signal controllers allows to switch from signal-centric strategies (for instance, resorting to TSP requests) towards vehicle-centric (Seredynski et al., 2015). The two SPaT-based controls that are researched in literature are the Green Light Optimal Speed Advisory (GLOSA) (Seredynski et al., 2013; Stebbins et al., 2016) and the Green Light Optimal Dwell Time Advisory (GLODTA) (Seredynski and Khadraoui, 2014). Both solutions have been conceived to mitigate stop-and-go driving. GLOSA does so by providing vehicles with speed guidance, while GLODTA reaches the goal by optimizing dwell time of PT vehicles (i.e. by occasionally holding the buses longer at bus stops). Consequently, performance of traffic flow of buses is improved without the need of changing traffic signal timings. As up to 20% more fuel is used to accelerate from a full stop to a speed of 8 kilometres per hour (in case of a passenger car), there are significant benefits of moving to stop-and-go or slow-and-go patterns. GLOSA has been studied in several projects and field operational tests for both cars and buses, e.g. PREDRIVE C2X (Katsaros et al., 2012), DRIVEC2X (Kraizewicz et al., 2012), simTD (Ress and Wiecker, 2016), MobiTraff (Seredynski and Khadraoui, 2015), Compass4D (Madsen et al., 2015). Extensions of GLOSA have been found in the literature in combination with adaptive signal control strategies (Bodenheimer et al., 2014), with vehicle platooning (Stebbins et al., 2016), and to generate fuel-efficiency speed profiles (Wan et al., 2016). Very limited works combine GLOSA with e-vehicles (e.g. Wu et al, 2015). GLODTA advises a prolonged dwell time at bus stops in order to avoid arriving at the next signalized intersection during a red phase (Seredynski and Khadraoui, 2015).

Both GLOSA and GLODTA strategies rely on Signal Phase and Timing (SPaT) data continuously communicated from controllers placed along the route. Furthermore, real-time positions of buses in the network are accessed through Automated Vehicle Location (AVL) systems to estimate the speed and the additional dwell times. However, the two aforementioned systems do not yet take into account battery charging requirements of electric buses with on route charging. Recently, the work of Giorgione et al. (2017) addressed this issue. The proposed eGLOSA instructs the driver to maintain a specific speed so that the bus traverses the next signalized intersection without stopping and affecting signal timings, and it further considers the energy consumption. On the other hand, eGLODTA determines whether additional dwell time should be advised, considering both schedule adherence criteria and on-route battery charging needs.

In this paper we investigate whether C-ITS-based solutions, and in particular GLODTA, can be adopted to reduce the need to resort to TSP and in combination with holding strategies, contribute to increase the regularity of the bus service.

This study can therefore be seen as an extension of the work of Giorgione et al. (2017), which has focused on introducing energy consumption in the operational objectives of e-bus systems on schedule-based services. We will instead include bus regularity objectives in frequency-based services. This work can also be seen as complementary to recent work of Seredynski and Viti (2018), where GLOSA and GLODTA have been studied to reduce the need for TSP, but for conventional bus systems.

3 Methodology

3.1 Modelling assumptions

Our modelling approach consists of two layers: the first represents the physical eco-system, consisting of 1) a traffic light system managed by a traffic management centre, 2) the bus system and 3) the charging infrastructure managed by the same bus operator. The second layer corresponds to the cooperative communication environment composed of interconnected vehicles communicating positions and priority levels. The goal of our approach is to manage efficiently three interacting components, i.e. 1) the in-vehicle control managed by a Driver Assistance System (DAS) dashboard supporting the bus drivers, 2) a signal control system regulating traffic and eventually providing priority to the buses, and 3) a centralised back-office system which takes care of the scheduling of buses and of e-bus charging.

Traffic lights are assumed as pre-phased, with a-priori stages, cycle times and green/red timings. We assume that all signals are equipped with Dynamic Short-Range Communication (DSRC, also known under the name of ETSI ITS-G5 in Europe), which allows infrastructure-to-vehicle communication within a range of around 200m) and provide SPaT information to all vehicles within this range. Each e-bus is equipped with AVL and APC systems, and it collects real-time information about locations and also about battery status of each e-bus. We assume that the back-office, via AVL information, seeks for cost-efficient use of e-charging infrastructure with minimisation of impact on operations, and optimised e-charging schedules.

Schedules are used as constraints to the operational times of buses so it is important to guarantee punctuality (for scheduled services) and/or regularity (for frequency-based services) in order to guarantee optimal charging operations (Rinaldi et al., 2018). On the other hand, change in charging plans may always occur during the day as the bus system remains unavoidably stochastic due to boarding and alighting operations, traffic congestion, incidents, etc. However, we leave the problem of re-computing optimal charging schedules due to operational delays to future research.

Since full charging takes approximately 6 minutes (Gallo et al., 2014), it is reasonable to assume that a bus leaving the terminal will be fully charged. On the other hand, buses are required to terminate their trip with at least 10% remaining battery to consider a safety margin to prevent the bus to stop while still on-route.

3.2 Overview of the model

We present a novel control strategy in which, when a vehicle gets sufficiently close to a traffic light to obtain SPaT information, the decision is not limited to traverse the next intersection during the green phase, but it involves the actual time headway between consecutive vehicles, in order to arrive evenly spaced as best as possible at stops, hence reducing the level of bunching and overall improve line regularity.

In particular, at stops where holding is applied (Time Control Points, or TCPs), holding time for regularity is determined by a simple rule subject to the forward and backward headways (Cats et al., 2011). In order to ensure that vehicles, by the time of their departure, will traverse the intersection without stopping, the additional time needed is estimated via GLODTA. In case of a late arrival, only GLODTA time is checked and triggered only if it results in time saving for the line.

In the control strategy developed, calls for green time extension and green recall are also considered, expecting to be in line with the findings of previous studies for need of weak TSP instead of strong TSP (Seredynski and Khadraoui, 2014).

3.3 Problem formulation

We represent the bus infrastructure through a directed graph, $G(N, L)$, where N is the node set and L the set of links. Individual links $l_i \in L$ are characterised by length D [m] and maximum speed $Vmax$ [km/h] information, while nodes $n_i \in N$ are subdivided into three categories: traffic light intersections, bus stops and bus terminal(s). Charging stations can be located at both terminals of a line, as well as at a single terminal (as it is the case of circular lines).

In the following we present the different controls that determine the trajectory of the bus along the route.

Bus holding: As primary objective, bus regularity should be sought in order to guarantee high quality of service for the passengers and for smooth and efficient charging operations at terminals. A well-established control strategy to regularise bus headways is holding control (Daganzo, 2009), in which buses are instructed to hold on a bus stop an additional time such that headway with the preceding and the succeeding vehicles is modified.

Holding time at bus stops is calculated according to the actual position of the vehicle and the maximum holding time allowed (a specific share of the planned headway). This time is straightforward for scheduled services, as arrival times at stops is pre-determined. For frequency-based services, the formula to calculate holding time is given as equation (1):

$$ET_{ijk} = \max\left(\min(term1, term2), AT_{ijk} + DT_{ijk}\right) \tag{1}$$

where $term1$ and $term2$ are respectively formulated as:

$$term1 = AT_{ijk-1} + \frac{AT_{imk+1} + SRT = AT_{ijk-1}}{2} \tag{2}$$

$$term2 = AT_{ijk-1} + \alpha PH \tag{3}$$

In the equations, AT_{ijk} and DT_{ijk} are the arrival time and the departure time of bus *k* at stop placed on link *i* and for line *j*. Note that this formula is general meaning that it considers also multiple lines to be coordinated. However, for simplicity's sake we will consider a single line control from now on. PH is the planned headway, while αis the threshold ratio parameter (ranges between 0.6-0.8). This formulation is in line with the one introduced by Cats et al. (2011).

GLODTA: Holding is an effective way of controlling buses for regularity objectives. As said this comes with a cost, as buses are delayed at stops, yielding to longer trip times and in turn more vehicles needed to operate at a certain service level. Similar to holding strategies, GLODTA introduces additional dwell times at bus stops, i.e. given that a bus stop is within the DSRC range distance from the next signalized intersection downstream, when the vehicle is ready for departure, the driver can be instructed to hold an additional amount of time if the average speed to reach the signal will allow him or her to traverse the next green phase. This means that eventual delays incurred at the signal are instead transferred to the upstream stop. The additional advantage is that the total number of stops for a trip is reduced, and hence less energy is consumed and emissions are expected to be reduced. Details on how GLODTA can be implemented in practice is given in (Seredynski and Khadraoui, 2014).

R-GLODTA: The aforementioned solutions have been developed to seek different objectives (regularity for the first and minimization of stops at traffic lights for the other two). However, holding and GLODTA are based on the same principle of delaying a vehicle by remaining for additional time at a stop. We explore a potential synergy of both by computing analytically, when a vehicle completes its dwell time, the holding time depending on its headway from the preceding and the succeeding vehicles together with the time needed to traverse the next green phase.

If the vehicle is either on time or late, when no holding is needed, in order to assist the operation by saving time at the link, only GLODTA is applied, again if needed.

In case of an early arrival, the vehicle should remain at the stop in order to restore regularity. From equation 1 both terms for actual holding time needed and the maximum holding are estimated. Then, we check if with either of the two the vehicle can hit a green phase. If one of the two times meets both regularity and green light criteria, it is selected and counts as a combined controller. If with both holding times we hit red then the holding time with the less estimated remaining time at the traffic light is selected and the controller counts simply as a regularity controller. This joint strategy, which we name R-GLODTA, is shown with the following Figure 1.

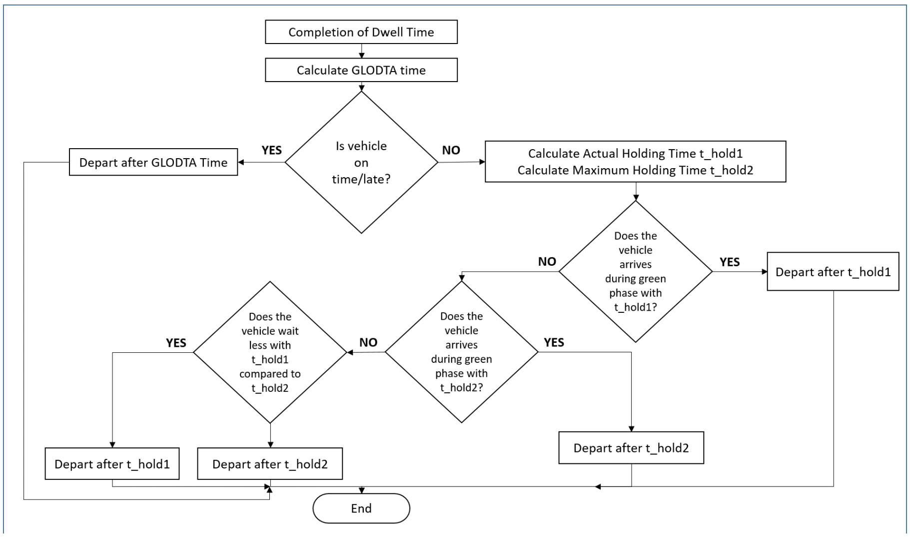


Figure 1. Operating rules of R-GLODTA

<u>TSP</u>: As already mentioned, Transit Signal Priority can be adopted at traffic lights to avoid buses to stop and in the same time provide some additional priority to the general traffic stream. This is obtained by detecting bus arrivals (via detectors or via C-ITS communication) and modifying green and red times. Green times can be anticipated (or extended) such that vehicles pass without modifying their planned trajectory. In our approach, before requesting a priority at traffic signals a bus attempts to use GLOSA and GLODTA advisory systems. That is, first a bus attempts to avoid stopping at signals by using uniquely the combination of the two systems. If this fails, priority request can be sent to the traffic controller.

3.4 Computational algorithm

We present here the whole procedure to apply our integrated control method:

Given

- Network layout (number of line segments, bus stop positions
- Traffic light position and signal timings
- Operational speeds of buses and their schedules

- Passenger demand profile determined as function of passenger load on each segment and dwell times at stops

CONTROLS

1. Apply GLODTA
   - IF distance between stop and next traffic light is less or equal than 200m
   - Calculate extra holding time Tglodta to pass on green (calculated at the end of the dwell time at the stop)
   - IF Tglodta>0 THEN apply GLODTA
2. R-GLODTA
   - IF distance between stop and next traffic light is less or equal than 200m
   - Calculate extra holding time Tglodta to pass on green (calculated at the end of the dwell time at the stop)
   - Calculate holding time using regularization strategy (1-3)
   - IF T(glodta+Holding)>0 THEN apply R-GLODTA
3. TSP
   - IF GLOSA or GLODTA cannot be applied (out of mix-max values) THEN
   - Check if above boundaries can be met with TSP (extend/anticipate green of max 5s)

4 Simulation study

The proposed algorithmic scheme is tested and evaluated by simulating an artificial high frequency line. Control is applied at specific stops of a bus line where high passenger demand and delays in terms of travel time are observed. We compare the new control criteria with independent application of holding and the DAS at the selected TCPs and a no-control case is used as a benchmark.

4.1 Simulation model

We developed a simulation environment in MATLAB. The basic elements of the code are the physical network and the passenger demand.

During simulation, there are two dimensions that are logged. Time and Passengers. Passengers enter and exit to the network via the stops along the line. The time passengers spend in the network is the time spending waiting for the next vehicle to board at stops and the in-vehicle time (the time between the origin stop and the destination stop including all intermediate stops).

In terms of time, the following information is recorded:

- Dispatching time from terminal;
- Riding time between stops;
- Arrival time at each stop;
- Dwell time at each stop;

- Departure time at each stop;

For passengers:

- The number of boarding passengers
- The number of alighting passengers
- The number of passengers on board

The main sources of stochasticity are the dispatching time, the riding time between stops and the arrival of passengers at stops. The actual times and number of passengers can be given and the system will give the results like no disruptions has happened.

To create a schedule, a matrix is created for the program with the arrival time at each stop for each trip. The calculation is based simply on adding the scheduled riding times between stops. It also exports an excel file to compare with actual times, which are sampled from lognormal distribution. First the mean and the variation are given as an input to calculate the scale and the shape parameter of the distribution. As mean, the scheduled riding time of the distance between the two stops is given for the desired variance, the deviation from the mean (95% of the scheduled riding time is recommended unless empirical data is available and both can be estimated).

Vehicles that arrive at the first stop arrive directly from the depot. In case of no chained trips then arrival times can be equal to the dispatching times. At the remaining stops, arrival time is equal to the departure time from the previous stop and the actual riding time between the stops. If overtaking is allowed then the vehicle's index should be monitored and all following headways should be calculated subject to the new position of the vehicles. If overtaking is not allowed, then after calculating the arrival time, the arrival time should be compared with the arrival time of the previous vehicle. If the current arrival time is smaller than the arrival time of the previous vehicle in order to assume that the bus followed the preceding vehicle and arrived together at the stop then the current arrival time should be set equal to the previous one and the additional time should be added to the previous riding time in order to have consistency in the sequence of calculations. Arrival based headway is the difference between the arrival time of the current and the previous trip.

4.2 Performance indicators

The main performance indicators used in this study are the adherence of headway of the line as well as total travel time and its variability. Moreover, we will also analyse the delay at the different intersections and the times the vehicles managed to pass through a green phase, in order to compare the results at both network level and at a local scale. These are the performance indicators selected for the study:

1. Regularity indicators: Coefficient of variation of headways; bunching;
2. Passengers' cost indicators: in-vehicle time; waiting time at stops;

3. Link performance indicators: stop frequency and delay at traffic light; average speed and travel time variance;
4. Energy consumption: average battery status at the end of the trip.

4.3 Case study

We tested the simulated controls for one of the busiest lines of the city of Luxembourg (Line 16, Figure 2).

Figure 2. Line 16 layout

The line consists of 19 stops in the eastbound direction and connects the new activity zone at the south part of the city with the city centre, the central business district of Kirchberg and finally the airport of Findel. This line provides also connection with the major transport hubs of the city (central railway station, Kirchberg multimodal

transport hub and the airport. The frequency of the line is 10min and articulated buses are used for the trip. The demand profile of the line is displayed in Figure 3.

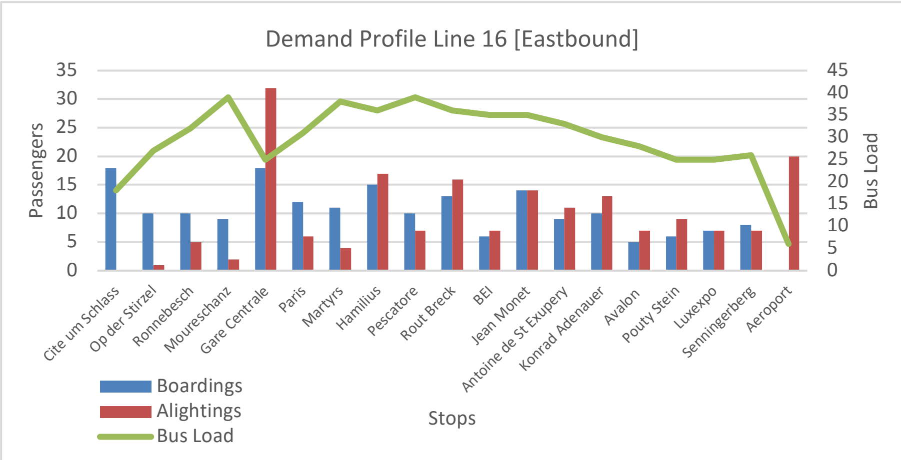


Figure 3. demand profile for eastbound direction

All intersections have been assumed equipped with TSP technology, and bus stops have been set as time control points (TCP). We assume that all traffic lights have the same signal program with cycle of 120sec (40 green and 80 red) with the red indication first at the simulation environment. No coordination has been considered between signals.

We simulated and compared 5 different scenarios (25 replications were conducted for each scenario):

1. No control: the e-buses are running without any C-ITS support and they do not receive any priority at signals;
2. Holding: the e-buses seek for headway regularisation via holding ta each bus stop;
3. GLODTA: when applicable, additional dwell time is added to the boarding-alighting time at each stop to avoid arriving during red at the next traffic light;
4. GLODTA+Holding: a combination of the two strategies;
5. GLODTA+Holding+TSP: additional to holding at the stop, priority is given at traffic lights.

4.4 Simulation results

Regularity: Figure 4 compares the behaviour of the coefficient of variation (CV) of headways for all simulated scenarios. It is clear from the results that headway variability improves when the controller accounts for regularity.

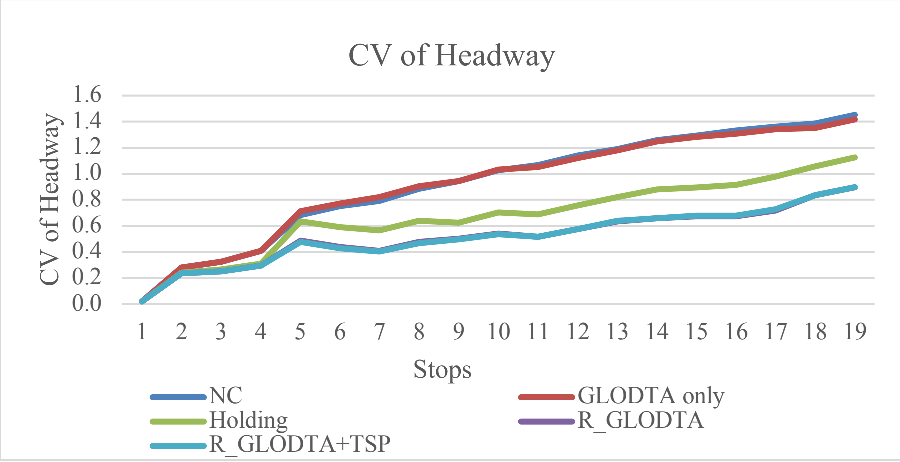


Figure 4. Coefficient of Variation (CV) of headways between buses

As one can see, the R-GLODTA outperforms both holding and simple GLODTA strategies, which straightforwardly do not show any significant improvement with respect to the no-control scenario. This is because it is more generous than the simple holding strategy when adding time, with the possibility to allow maximum holding time to ensure also the GLODTA stop-avoidance criterion. It should also be noted that in terms of CV improvement, R-GLODTA shows similar achievements then with TSP, hence on the basis of bus regularity, TSP does not provide any additional gain.

Passengers' costs: Regularising headways comes with a price: it penalizes the passengers on board with extra in-vehicle delay compared to simple holding, as shown in Table 1. On the other hand, vehicle bunching as well as passengers' waiting times are significantly reduced.

Table 1. Bus line and passengers' indicators

	CV Line	Bunching	Waiting time	In vehicle time
NC	0,92	0,546	150,17	152,18
GLODTA	0,92	0,53	150,6	154,22
HOLDING	0,66	0,37	150,4	161,8
R_GLODTA	0,52	0,27	145,7	162,5
R_GLODTA+TSP	0,52	0,26	145,6	162,55

Link performance: Table 2 shows how R-GLODTA is also very effective in reducing the number of stops, waiting time and overall increase the average speed at the link if compared to no-control and single control strategies. Clearly in this case TSP provides some additional gain but this is relatively marginal.

Table 2. Link performance indicators

	Stop Frequency at traffic light	Average Waiting Time at Traffic Light	Average Speed
NC	0,329	6,76	21,8
GLODTA	0,261	3,88	22,1
HOLDING	0,314	6,62	21,7
R_GLODTA	0,170	2,81	23,2
R_GLODTA+TSP	0,163	2,67	23,3

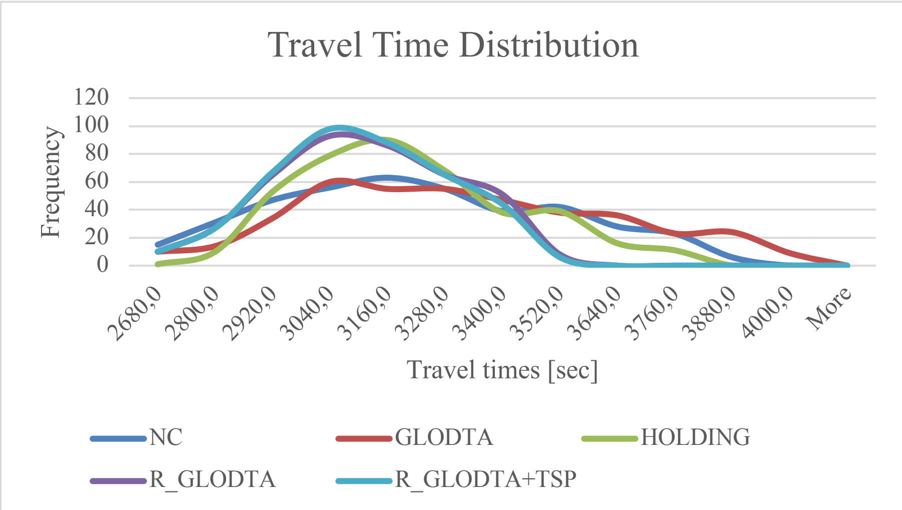
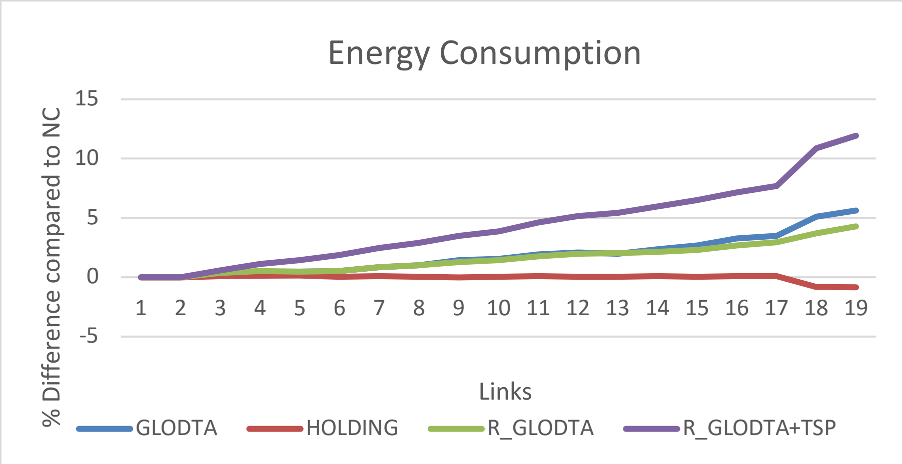


Figure 6. Trip time distribution for each control strategy

Figure 6 shows the trip time distribution for each scenario. Again, R-GLODTA shows very similar performances with or without resorting to TSP, which one more time indicates that such control strategy may be effectively applied without taking away capacity from opposing traffic streams.

Energy consumption: finally, we investigate the impact of adopting different control strategies affect the electrical energy consumption. We adopted the energy consumption model used in Giorgione et al. (2017), slightly adapted to consider additional traction force needed to perform bus accelerations. Figure 7 provides the trend in terms of average energy saved with respect to the no-controlled scenario.



As one can observe, holding provides no gain with respect to the NC scenario, and actually it slightly increases the total energy consumed due to the additional holding times. All other strategies are positively impacting energy consumption, with R-GLODTA with TSP strongly outperforming the other methods and reaching more than 11% less energy consumption with respect to the no-control scenario.

A final analysis is performed to check how many times the different strategies are adopted in the simulated scenarios. Figure 5 shows the share of each control decision, i.e. when each control was needed.

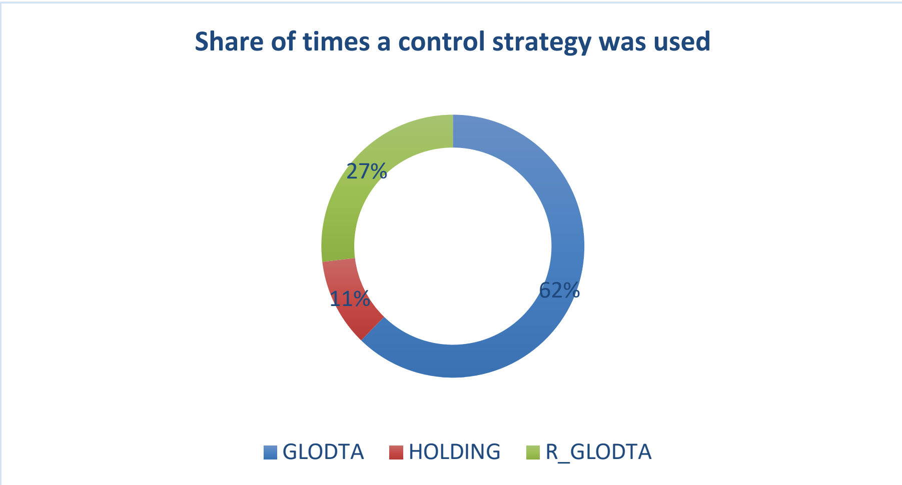


Figure 5. Share of times each control strategy was used

As one can observe, fixing regularity was needed in around 38% of the cases, when vehicles were early, while in all other cases only GLODTA was used to

ensure that vehicle would pass during green. In the cases that holding was needed R-GLODTA was used more frequently used than simple holding ignoring the indication at the intersection downstream. It should be mentioned that in the simulated environment, control was needed approximately 48% of times.

5 Conclusions

This paper presented a novel control strategy that combines a Cooperative ITS-based driving assistance system, namely Green Light Optimal Speed Adaptation (GLODTA) with bus holding control at bus stops. In particular, benefits of this integrated strategy for the deployment of electrical buses is presented through a realistic simulation scenario.

The logic behind this integrated method is that bus holding can effectively improve different objectives, namely 1) bus regularity performance, 2) passengers costs, 3) trip performances, and 4) energy consumption.

Using a case study inspired by a real line in Luxembourg city, we showed that significant gains are achieved on all four performance indicators. Additionally, we show that the novel R-GLODTA strategy provides effective improvements even when Transit Signal Priorities are not provided to buses.

Future research will focus on testing if similar conclusions are confirmed using the other C-ITS-based solution, i.e. GLOSA, and will extend the current simulation to multiple interacting lines.

Acknowledgements: This research is supported by the Fonds National de Recherche (FNR) of Luxembourg through the CORE grant eCoBus C16/IS/11349329.

References

Bodenheimer, R., Brauer, A., Eckhoff, D., German, R.: Enabling GLOSA for adaptive traffic lights. In: Proc. IEEE Vehicular Networking Conference (VNC) (2014) 167-174

O. Cats, A. Larijani, H. Koutsopoulos, and W. Burghout, “Impacts of Holding Control Strategies on Transit Performance,” Transp. Res. Rec. J. Transp. Res. Board, vol. 2216, pp. 51–58, Dec. 2011.

O. Cats, A. Larijani, Á. Ólafsdóttir, W. Burghout, I. Andréasson, and H. Koutsopoulos, “Bus-Holding Control Strategies,” Transp. Res. Rec. J. Transp. Res. Board, vol. 2274, pp. 100–108, Oct. 2012

Daganzo C.F. (2009) A headway-based approach to eliminate bus bunching: Systematic analysis and comparisons. *Transportation Research Part B: Methodological*, **43**(10), pp. 913-921.

Fusco G., Alessandrini A., Colombaroni C., Valentini M.P. (2012) A model for transit design with choice of electric charging system. *Procedia - Social and Behavioral Sciences*, vol. **87**, pp. 234-249.

Gallo, J.B., Bloch-Rubin, T., Tomific, J. (2014) Peak demand charges and electric transit buses. Technical report, U.S. Department of Transportation.

Giorgione G., Viti F., Rinaldi M., Laskaris G., Seredynski M. (2017). Experimental analysis of eGLOSA and eGLODTA control strategies. In IEEE Models and Technologes for ITS, June 2017, Naples, Italy.

Katsaros, K., Kernchen, R., Dianati, M., Rieck, D., Zinoviou, C. (2012). Application of vehicular communications for improving the efficiency of traffic in urban areas. *Wireless Communication & Mobile Computing*, Vol. **11**(12), pp. 18-22

Krajzewicz, D., Bieker, L., Erdmann, J.: Preparing simulative evaluation of the GLOSA application. In: Proc. 19th ITS World Congress. (2012)

Lajunen A. (2014). Energy consumption and cost-benefit analysis of hybrid and electric city buses. Transportation Research Part C Emerging Technologies **38**, pp. 1–15.

Laskaris G., Cats O., Jenelius E., Viti F. (2016) A holding decision rule based on passenger travel cost. Proceedings of the IEEE-ITS Conference 2016, November 2016, Rio de Janeiro.

Li L., Zhang Y., Yang C., Yan B., Martinez C.M. (2016) Model predictive control-based efficient energy recovery control strategy for regenerative braking system of hybrid electric bus. *Energy Conversion and Management*, **111**, pp. 299-314.

Madsen, A.T., van den Bosch, N., Vreeswijk, J.: Advanced public transport priority solutions in Copenhagen. In: Proc. 22nd ITS World Congress. (2015)

Peng J., He H., Xiong R. (2017) Rule based energy management strategy for a series of parallel plug-in hybrid electric bus optimized by dynamic programming. *Applied Energy*, Vol. **185**, pp. 1633-1643.

Pternea M., Kepaptsoglou K., Karlaftis M. (2015) Sustainable urban transit network design. *Transportation Research Part A: Policy and Practice*, **77**, pp. 276-291.

Ress C., Wiecker M., Evaluating the Potential of V2X Communication for Road Safety and Efficiency. ATZ worldwide 118(1) (2016) 16-21

Rinaldi M., Parisi F., Laskaris G., D'Ariano A., Viti F. (2018). Optimal dispatching of electric and hybrid buses subject to scheduling and charging constraints. Submitted to the 21st International Conference on Intelligent Transport Systems, November 2018, Hawaii, US.

Rogge, M., Wollny, S., Sauer, D.U.: Fast charging battery buses for the electrification of urban public transport-a feasibility study focusing on charging infrastructure. Energies **8**(5) (2015) 4587-4606

Seredynski M., B. Dorronsoro, and D. Khadraoui (2013). Comparison of green light optimal speed advisory approaches. In Intelligent Transportation Systems-(ITSC), 16th International IEEE Conference on, 2013, pp. 2187–2192.

Seredynski M., Khadraoui D. (2014). Complementing transit signal priority with speed and dwell time extension advisories. In Intelligent Transportation Systems (ITSC), IEEE 17th International Conference on, 2014, pp. 1009–1014.

Seredynski M., Khadraoui D., Viti F. (2015) Signal phase and timing (SPaT) for cooperative public transport priority measures. Proceedings of the 22nd ITS World Congress, October 2015, Bordeaux.

Seredynski M., Viti F. (2016). A Survey of Cooperative ITS for Next Generation Public Transport Systems. In Proceedings of the 19th International Conference on Intelligent Transport Systems, November 2016, Rio de Janeiro, Brazil.

Seredynski M., Viti F. (2018). Towards Cooperative Bus Priority at Traffic Signals. Sumbitted *to IEEE Transactions on ITS*.

Stebbins S., Kim J., Hickman M., Vu, H.L. (2016). Characterizing Green Light Optimal Speed Advisory Trajectories for Platoon-Based Optimization. TRB 95th Annual Meeting Compendium of Papers.

Wan, N., Vahidi, A., Luckow, A. (2016). Optimal speed advisory for connected vehicles in arterial roads and the impact on mixed traffic. *Transportation Research Part C* Vol. **69**, pp. 548-563.

Wu, X., He, X., Yu, G., Harmandayan, A., Wang, Y.: Energy-optimal speed control for electric vehicles on signalized arterials. IEEE Transactions on Intelligent Transportation Systems **16**(5) (2015)

Xylia, M., Leduc, S., Patrizio, P., Kraxner, F., Silveira, S. (2017) Locating charging infrastructure for electric buses in Stockholm. *Transportation Research Part C: Emerging Technologies*, **78**, pp. 183-200.

ZeEUS project (FP7), http://zeeus.eu (last access: May 2018)