TOWARDS OPTIMIZED DEPLOYMENT OF ELECTRIC BUS SYSTEMS USING COOPERATIVE ITS

Georgios Laskaris, Corresponding Author
Faculty of Science, Technology and Communication
University of Luxembourg
6, Avenue de la Fonte L-4364 Esch-sur-Alzette
Email: georgios.Laskaris@uni.lu

Marcin SEREDYNSKI
Volvo E-Bus Competence Center
Centre Poids Lourds Sàrl
251, Route de Luxembourg
LU - 3378 Livange
Email: marcin.seredynski@consultant.volvo.com

Francesco VITI
Faculty of Science, Technology and Communication
University of Luxembourg
6, Avenue de la Fonte L-4364 Esch-sur-Alzette
Email: francesco.viti@uni.lu

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ABSTRACT
In this paper we analyze 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

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.
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 (*1*).
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 a C-ITS-based driver assistance system, namely the 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.

LITERATURE REVIEW

PT systems consisting of e-buses reduce emissions, energy use, and noise as well as offer smoother rides (*2*). 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 (*3*). 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 (*4*). 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 (*5*). 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 (*6*). The existing research efforts currently focus on developing a proper system design such as deploying strategic locations of charging stations (*7*, *8*). At operational levels, energy efficiency is currently addressed via energy management strategies for the engine (*9*), and regenerative breaking technologies (*10*).
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) (*11*). Currently, in the literature, TSP, together with holding control strategies (*12*) 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 strategy has proven to be effective in restoring regularity and maintain a smooth operation (*13–17*). However, 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 (*18*). The two SPaT-based controls that are researched in literature are the Green Light Optimal Speed Advisory (GLOSA) (*19*, *20*) and the Green Light Optimal Dwell Time Advisory (GLODTA) (*21*). 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 (*22*), DRIVEC2X (*23*), simTD (*24*), MobiTraff (*18*), Compass4D (*18*) Extensions of GLOSA have been found in the literature in combination with adaptive signal control strategies (*25*), with vehicle platooning (*20*), and to generate fuel-efficiency speed profiles (*26*). Very limited works combine GLOSA with e-vehicles (*27*). GLODTA advises a prolonged dwell time at bus stops in order to avoid arriving at the next signalized intersection during a red phase (*18*).

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. (*28*) 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. (*28*), 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 (*1*), where GLOSA and GLODTA have been studied to reduce the need for TSP, but for conventional bus systems.

METHODOLOGY

Modelling assumptions

Our modelling approach consists of two layers: the first represents the physical eco-system, consisting of:

- a traffic light system managed by a traffic management centre;
- the bus system; and
- 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: 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 bus operation 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 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 (*29*). 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 (*4*), 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.

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 (*21*).

Problem Formulation

We assume a bus line *i*, the route of which consists of J stops and there are K trips conducted. Between stops, there are J-1 links that connect the stops with different lengths. Links may contain a signalized intersection, the distance of which from the upstream bus stop is known. A fixed cycle is assumed for all traffic lights. All trips are conducted with the same vehicle type with similar characteristics and same average speed.

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

Holding strategy

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 (*14*), 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.

The holding criterion chosen for this study is the criterion used by Cats et al (*16*). The criterion has been compared with other holding strategies using simulation for frequency-based services and has proven to be superior (*16*, *30*). The criterion is based on the actual headway of the vehicle subject to its preceding and succeeding buses. Additionally, the maximum allowed holding time is limited to a specific share of the planned headway. The formula to calculate departure (exit) time ET_{ijk} is given as equation (1):

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

Where *term 1* and *term 2* are respectively formulated as:

$$term1 = AT_{ijk-1} + \frac{AT_{imk+1} + SRT + AT_{ijk-1}}{2} \quad (2)$$
$$term2 = AT_{ijk-1} + \alpha PH \quad (3)$$

In the equations, AT_{ijk} and DT_{ijk} are the arrival time and the dwell time of bus *k* at stop placed on link *j* and for line *i*, respectively. $term1$ is estimated as the average between the arrival time of the previous vehicle AT_{ijk-1} and the arrival time of the following vehicle *k+1*. We estimate the arrival time of the succeeding vehicle *k+1* from the current stop by summing the scheduled riding time *SRT* between the last visited stop *m* and the current stop *j* and the arrival time at the last visited stop *m* AT_{imk+1}. *PH* is the planned headway, while α is the threshold ratio parameter that limits the maximum allowed holding. Threshold ratio parameter ranges between 0.6-0.8 (*13*, *16*). For simplicity's sake, we will consider a single line control from now on.

GLODTA

Holding is an effective way of controlling buses for regularity objectives. As aforementioned, 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. Specifically, 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 (*21*).

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.

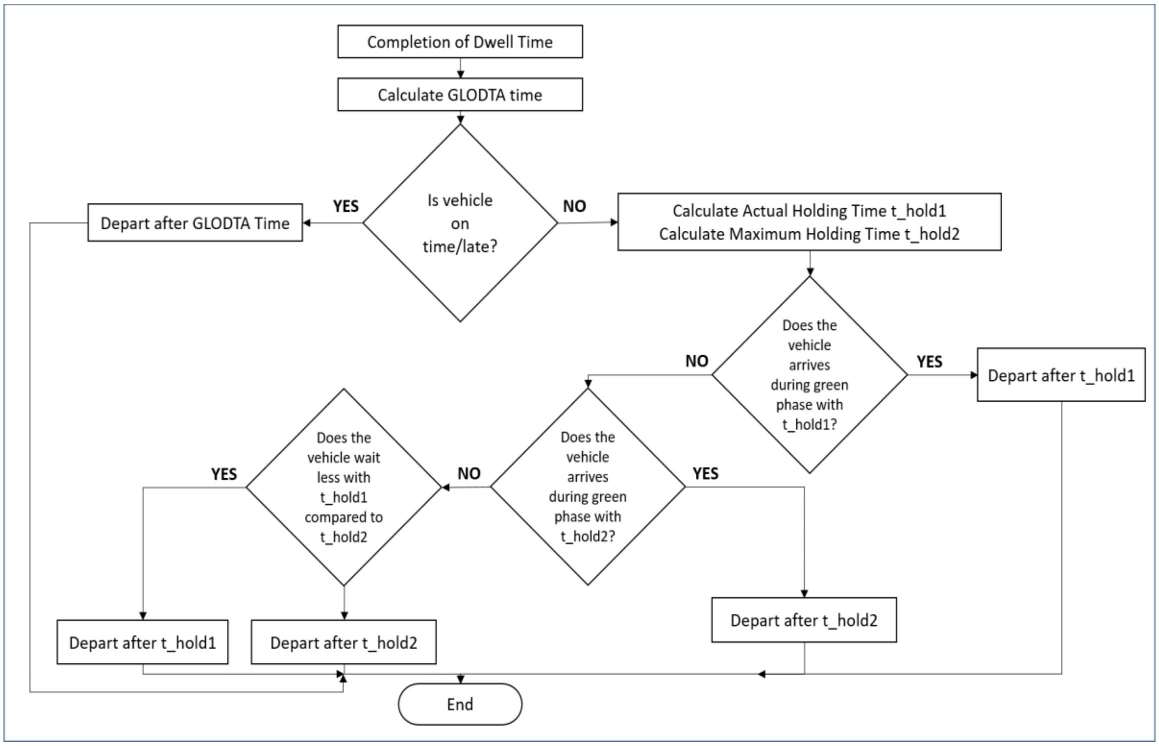

FIGURE 1 Operating rules of R-GLODTA

Transit Signal Priority

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.

Computational Algorithm

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

Given

- Network layout (number of line segments, bus stop positions);
- Traffic light position and signal timings;
- Operational speeds of buses and their scheduled riding time; and
- Passenger demand profile in terms of arrival rates per OD pair at each bus stop.

CONTROLS

1. GLODTA

IF
    distance between stop and next traffic light is less or equal than 200m
THEN
    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
AND
    vehicle early or on time
THEN
    Calculate extra holding time Tglodta to pass on green (calculated at the end of the dwell time at the stop)
ELSE
    Calculate holding time using regularization strategy (1-3)
IF
    holding time within Tglodta interval to pass on green
THEN
    use holding time
ELSE
    depart for the holding time with the least expected waiting time at traffic light

3. TSP

IF
    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)

SIMULATION STUDY

The proposed algorithmic scheme is tested and evaluated by simulating a 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.

Simulation Environment

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;
- Actual riding time between stops;
- Arrival time at each stop;
- Dwell time at each stop; and
- Departure time at each stop;

For passengers:

- The number of boarding passengers;
- The number of alighting passengers; and
- 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. Dispatching times are drawn by Gamma distribution given the planned headway between departures and the user can increase the variability by changing the shape and the size of the distribution. For the current setup, we assume that vehicles are dispatched perfectly regular.

The calculation of actual riding times on the links between stops depends on the existence of a signalized intersection. If there is no signalized intersection, the riding time is sampled by lognormal distribution with given inputs the scheduled riding time and the desired standard deviation. Since empirical data is not available, the standard deviation is set to 20% of the scheduled riding time. In case of a signalized intersection, actual speed is sampled from a normal distribution, getting values between a minimum and a maximum speed given by the user. If the vehicle pass on green with its actual speed, continues until the next stop and the actual riding time is registered. In case of a stop on a red, the waiting time at red is registered and vehicle continues after resampling a new speed. The actual riding time is the sum of the running times prior and after the intersection and the waiting time at the traffic light.

We assume that passengers arrive at stops randomly following Poisson distribution. The simulator gets as input the arrival rate per OD pair and during simulation the actual headway in order to generate the number of passengers at each stop. Alighting passengers at each stop are the share of passengers boarded at the previous stop with destination the specific stop. Occupancy of the bus is defined at each stop by the numbers of boarding and alighting passengers and the last recorded occupancy.

During simulation each trip is generated and arrives at the first stop at its dispatching time. At each stop, after the arrival time of the vehicle is registered and the actual headway is calculated and boarding passengers are estimated. Dwell time is calculated as the sum of the product of the boarding and alighting passengers with the corresponding rate with a constant that represents a potential delay at the stop. After the completion of dwell time, if no control is applied the vehicle departs and the departure time is registered. If control is applied the corresponding controller is triggered and returns the additional time a vehicle is help at the stop. If the controller includes a TSP call, the time the green phase of the next traffic light is also returned to be added to the cycle. Overtaking is not allowed. In the case of bunched vehicles, the successor cannot depart prior to its preceding vehicle. As a recovery strategy, the following vehicle departs after an additional time to increase the headway between vehicles.

Each replication simulates a 3-hour operation of the bus lines. For each replication, the first three and the last three trips are excluded from the analysis as they run deterministically and constitute the warm up and the cool down period of the simulation.

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. The performance indicators selected for the study are the following:

Regularity indicators: Coefficient of variation of headways; bunching;

Passengers' cost indicators: in-vehicle time; waiting time at stops;

Link performance indicators: stop frequency and delay at traffic light; average speed and travel time variance;

Energy consumption: average battery status at the end of the trip.

Case Study

We tested the simulated controls for one of the busiest lines of the city of Luxembourg, Line 16. The route of the line is depicted in Figure 2.

FIGURE 2 Line 16, Luxembourg City

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.

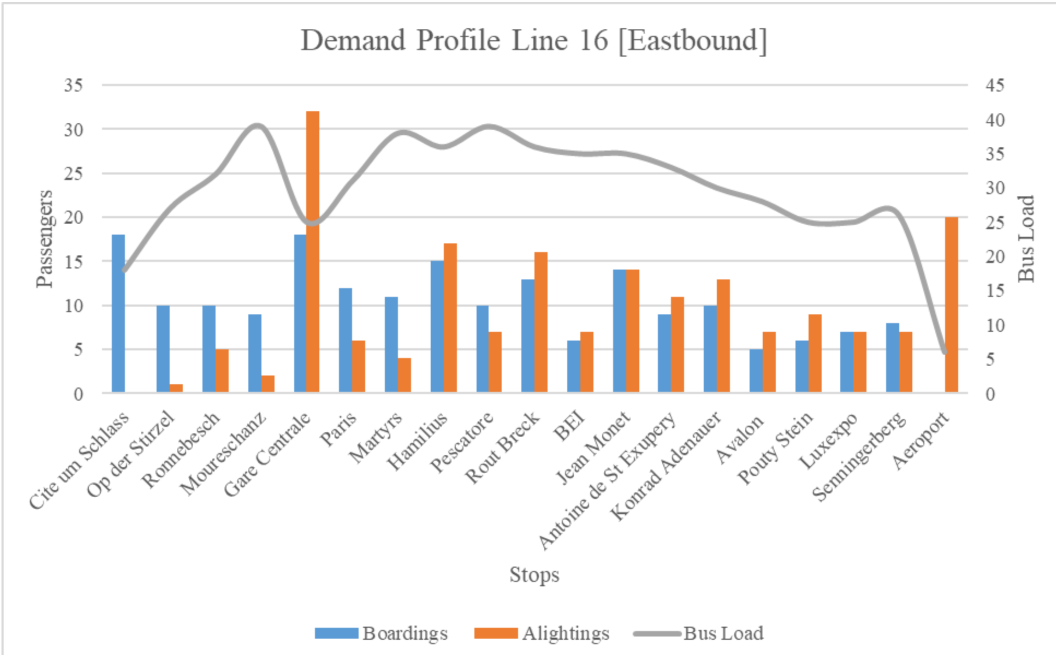

FIGURE 3 Demand Profile of Line 16

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 (80 green and 40 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):

- No Control: the e-buses are running without any C-ITS support and they do not receive any priority at signals;
- Holding: the e-buses seek for headway regularisation via holding at each bus stop;
- 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;
- R-GLODTA: a combination of the two strategies;
- R-GLODTA +TSP: additional to holding at the stop, priority is given at traffic lights.

SIMULATION RESULTS

Line Performance Indicators

An index of the variability of headway at each stop but also for the line is the coefficient of variation of headway (*31*). Coefficient of Variation of headway is the ratio of the standard deviarion over the average headway. 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.

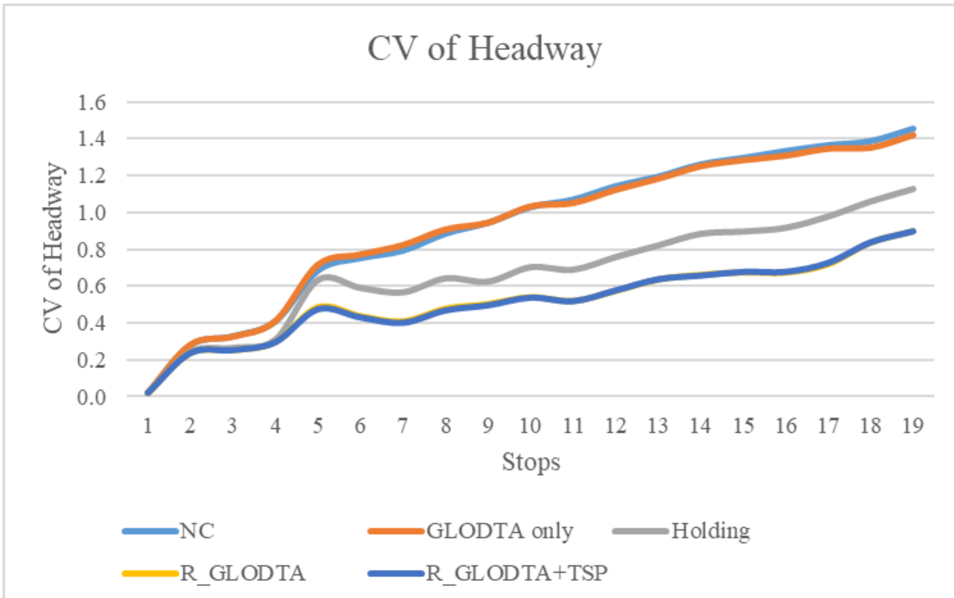

FIGURE 4 Coefficient of Variation (CV) at stops for the different scenarios

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.

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 Performance Indicators of line 16

Scenario	CV Line	Bunching	Waiting time [sec]	In vehicle time [sec]
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

Scenarios	Stop Frequency at traffic light	Average Waiting Time at Traffic Light [sec]	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

Travel Time

In general, a travel time distribution with less variability allows to the operator to create a more robust schedule and schedule the number of vehicles needed. Figure 5 shows the trip time distribution for each scenario. As shown in the figure with control strategies that account for line regularity, the objective of travel time with reduced variability is achieved. 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. On the contrary, by reducing the number of stops at traffic light alone (GLODTA scenario) cannot guarantee to a stable travel time distribution.

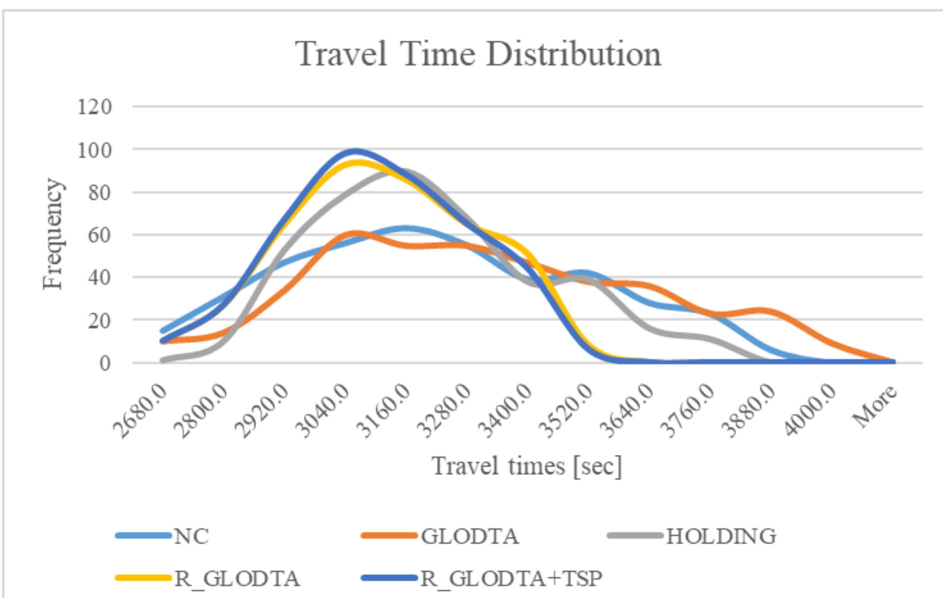

FIGURE 5 Travel time distribution for each scenario

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. (*28*), slightly adapted to consider additional traction force needed to perform bus accelerations. Figure 6 provides the trend in terms of average energy saved with respect to the no-controlled scenario.

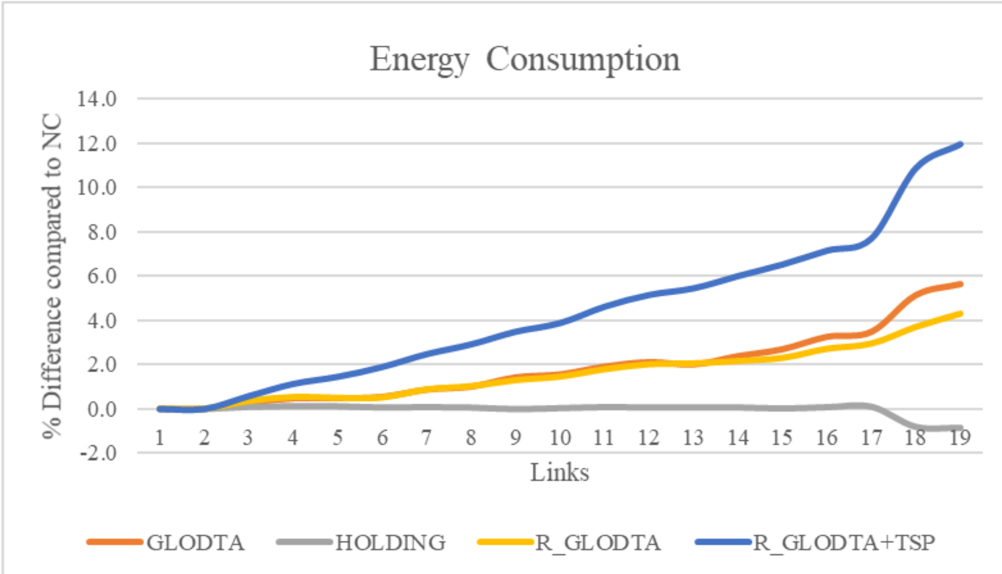

FIGURE 6 Energy consumption for each scenario

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.

Controller Performance

A final analysis is performed to check how many times the different strategies are adopted in the simulated scenarios. Figure 8 shows the share of each control decision, i.e. when each control was needed. As one can observe, fixing regularity was needed in around 38% of the controlled 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.

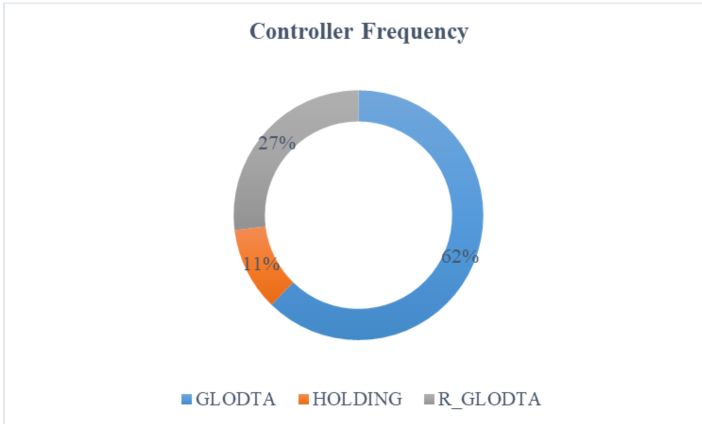

FIGURE 8 Share of times each control strategy was used

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.

AUTHOR CONTRIBUTION STATEMENT

"The authors confirm contribution to the paper as follows: study conception and design: G. Laskaris, M.Seredynski, F. Viti; model(s) formulation and implementation: G. Laskaris, F. Viti; analysis and interpretation of results G. Laskaris, F. Viti; draft manuscript preparation: G. Laskaris, M.Seredynski, F. Viti. All authors reviewed the results and approved the final version of the manuscript."

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