Paper #648

Minimising the impact of public transport on climate change

Marcin Seredynski
E-Bus Competence Center, Livange, Luxembourg, seredynski@ieee.org

Public transport (PT) will always remain a backbone of urban mobility due to its space and energy efficiency making it the most sustainable way of traveling. In smart cities PT use is driven by "carrot" initiatives rather than "stick" policies. The emerging technologies—electrification, connectivity, and automation—allow direct reductions of emissions of greenhouse gases, noise, and pollutants. However, the main environmental and societal gains are indirect via modal shift from cars to PT. That is, a combination of the technologies and traffic priority measures can make PT an attractive choice, boosting patronage and reducing car dependency. This paper illustrates interplay between technologies and assesses their impact. An example of how environmental, economic, and societal performance of full hybrid buses can be boosted by connectivity and geofencing is given.

Keywords: climate change, public transport, electromobility, automation

1. Introduction

Public transport (PT) represents a fraction of energy use, greenhouse gas (GHG) and pollutants emissions of comparable travel in cars. Therefore, successful PT is essential for transport emissions reduction strategy [1]. When being an attractive option, it encourages citizens to use their cars less, consequently reducing congestion, travel time, GHG emissions, and energy use. However, if PT vehicles are to compete with cars, they must be fast, reliable, frequent, comfortable and serve on properly designed routes. Unfortunately, as most cities are planned for private cars, it is very challenging for PT to become a viable alternative [1].

Electrification, digitalisation, and connectivity offer new ways to make PT more attractive. Driveline electrification curbs emissions (noise, GHG, and pollutants). If combined with battery energy storage it also reduces energy consumption. Connectivity and digitalisation allow optimising PT operations by supporting on-time performance, real-time passenger information and fleet management. However, true environmental and societal benefits of the new technologies and policies can only be assessed when looking at the entire mobility system (Fig. 1). Focusing only on a single element fails to measure the impact due to externalities. For instance, efficiency improvements of passenger cars might lead to its increased use (due to better fuel economy), which offsets benefits of the improvement [2] (rebound effect). On the other hand, PT improvements such as fleet electrification, signal priority, and bus lanes have positive externalities (increased ridership due to improved service quality, Fig. 1c). Same applies to policies. For instance, abolishing fares from PT has very limited impact on reducing car travel and often attracts people who would normally use active modes such as walking and cycling [3]. GHG emissions are one of the most significant driver of climate change. Tank-to-wheels (TTW) analysis addresses only local environmental problems such as noise and pollutants [4]. Climate change is global problem. Hence, when comparing GHG emissions from different powertrains, well-to-wheels (WTW) analysis is required rather than TTW (Fig. 1b). This means that GHG emissions of full electric vehicles depend on country's electricity generation mix [4].

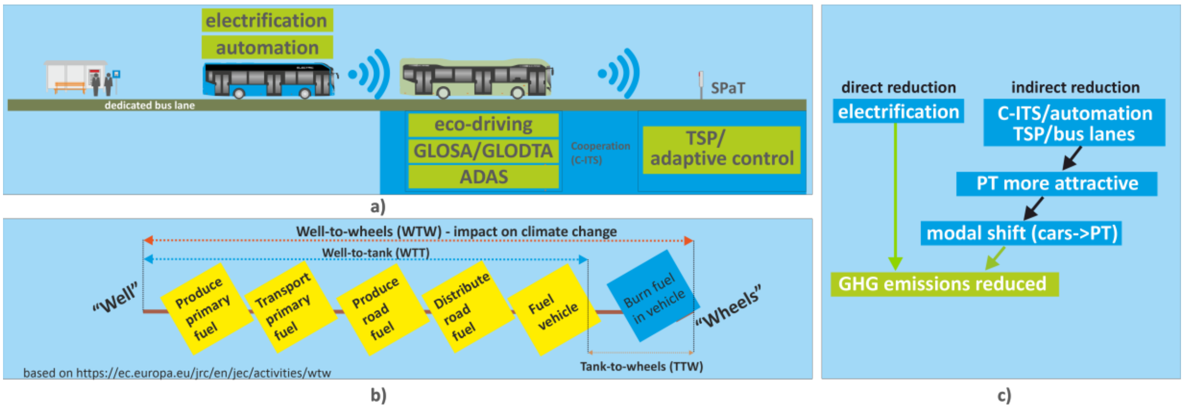

Figure 1 PT innovations (a), well-to-wheels analysis (b), direct and indirect GHG reductions via PT (c).

Future PT systems will take advantage of applications developed under the umbrella of cooperative intelligent transportation systems (C-ITS) [5]. C-ITS coupled with automation will enable coordinating movement of vehicles, increasing traffic efficiency, road safety, and comfort of driving. Such connected and autonomous vehicles (CAVs) will allow shifting away from use-optimum to system-optimum, thus minimising total energy and emissions from urban mobility. However, as CAVs will improve traffic flows by better utilisation of the existing road infrastructure, they will increase total miles traveled by private cars (via induced demand). Hence, if additional measures such as congestion pricing are not implemented, private CAVs will increase car use at the expense of PT.

The next section explains why significant direct GHG reductions via bus technologies can be achieved via full or partial electrification (full electrics, full hybrids) and with biofuels. Section 2 describes C-ITS/automation potentials to optimise PT operations. Section 3 shows how connectivity, and geofencing can improve environmental and societal benefits of the full hybrid bus technology.

2. Bus technologies

PT fleet renewal should have two main goals. The first one is to make PT more attractive by reducing emissions of noise and pollutants from the new vehicles, thus improving passenger experience as well as for pedestrians and outdoor diners. This indirectly decarbonises transportation through modal shift from cars to PT. The second goal is direct decarbonisation via driveline electrification or introduction of biofuels. Second generation biofuels derived from renewable byproducts and organic waste do not compete with food production, forestry or other land use [4]. However, as they remain a niche, electrification is the main strategy to decarbonise PT. Full electric buses (e-buses) are the best choice to achieve the two goals, followed by full hybrids. Due to battery-charging constraints [6,7], transition to electric-only PT will be gradual. That is, in the next years fleet renewals will not be composed of e-buses only. The transition path is summarised in Fig. 2.

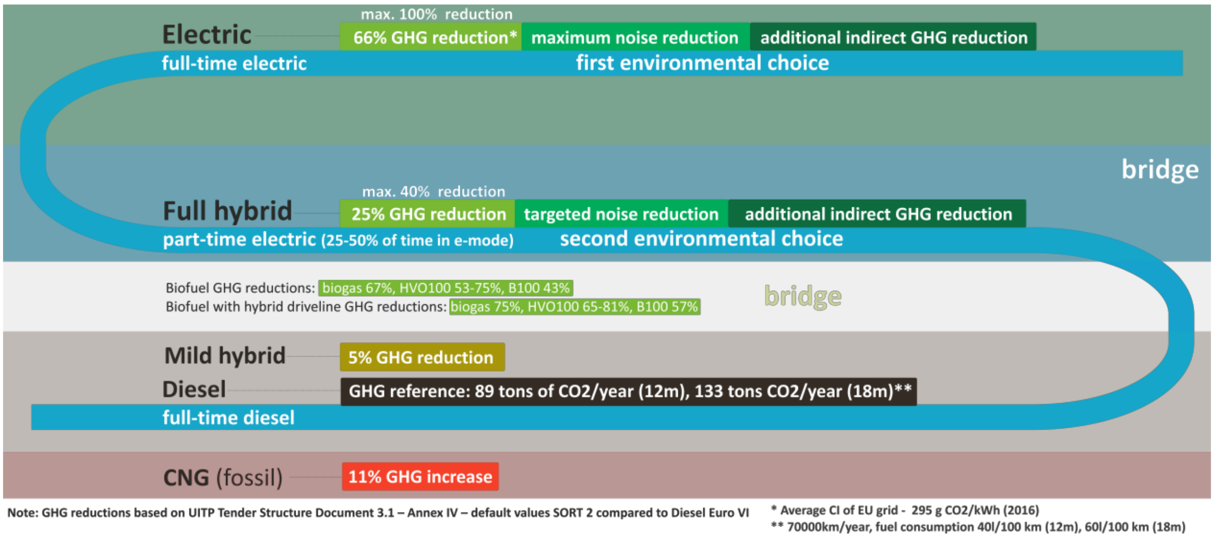

Figure 2 Path towards zero WTW emissions PT operations.

While e-buses are considered “green”, their full GHG reductions potential is in most places many years away. It depends on the carbon intensity (CI) of electricity generation—e-buses can reduce WTW GHG emissions up to 100% (if electricity is generated from renewables). Assuming operating values given in Fig. 2, it means up to 133 tons of CO2 less per year vs. a diesel bus. With an average EU mix (295g CO2eq/kWh) the reduction today is almost 70% (93 tons of CO2). CI decreases each year thanks to the increasing share of renewables in the energy mix.

Full hybrids are the second-best environmental choice. Their average GHG reduction of 25% means saving of up to 33 tons of CO2 annually per bus. In hilly routes (very high energy recover) it can go up to 40% (53 tons). From passenger perspective, they are part-time electric as they typically spend from 25 to 50% of their operating time in electric mode and usually drive between 10 and 30% of distance in zero tailpipe emission mode concentrated around noise-sensitive areas such as bus stops. Hence, they also contribute to indirect GHG reduction by making PT more attractive. This means that full hybrid buses are a bridge technology providing compromise between electrification benefits and operating flexibility.

High-power electric machine (EM) is the main enabler of the reductions offered by electric and full hybrid buses. It allows high energy recovery (also referred to as self-charging). For instance, it reduces energy consumption for traction of e-buses by on average 30%. High-power EM also provides energy-efficient electric propulsion. An e-bus maximises these benefits by using the highest power EM (>160 kW) and driving in electric mode only. A full hybrid bus applies high power EM (>100 kW), but propulsion role is split between EM and a diesel engine. That is, it drives in either pure electric mode, or in a hybrid mode. Mild hybrids appeared in the market very recently. They have conventional (not downsized) diesel engine with a low voltage (48V) battery and small EM (<20 kW). As a result, energy recovery is low and only diesel-dominated hybrid driving mode is available. Consequently, they deliver only slight energy/GHG emissions reductions and do not provide noise/comfort benefits to passengers and pedestrians. The impact of specific level of electrification is summarised in Fig. 3.

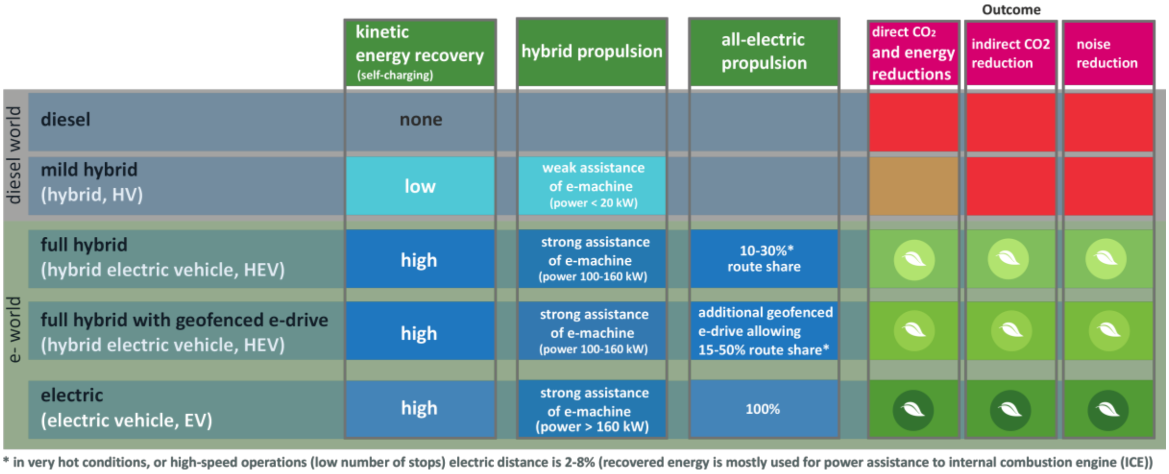

Figure 3 Levels of bus electrification.

Mild hybrids are often confused with full hybrids due lack of public awareness about differences in environmental and societal impact of various levels of electrification. They are becoming a popular choice as they come with the "hybrid" label (satisfying green marketing needs) for just slightly higher purchase price than diesel buses. Today externalities are not included in product price—as it does not reflect the true costs and benefits—market failure situation is created. That is, unless full hybrids are supported by PT authorities, CNG/diesel/mild hybrids are purchased instead of full hybrids.

Battery e-buses reduce GHG emissions even with energy having high CI. Fuel cell e-buses (FCEB) can only reduce these emissions with green hydrogen (produced from renewable energy and electrolysis). This requirement is a consequence of their low energy efficiency (see Fig. 4).

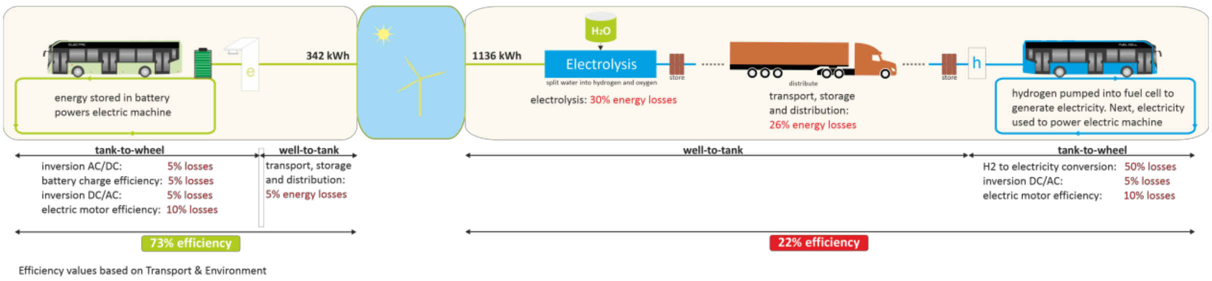

Figure 4 Battery electric vs. fuel cell electric bus driving 250km.

To drive 250 km with medium auxiliaries load a battery e-bus requires around 340 kWh, while FCEB needs approximately 1100 kWh. In addition, due to significant energy loses, only surplus renewable electricity produced during hours of slack demand shall be used to produce hydrogen. As today majority of hydrogen is produced from fossil fuels, FCEB remain a niche. Their advantage (higher range) is also diminishing over time due to increasing battery capacity—soon allowing battery-electric e-buses covering all types of city operations. Therefore, FCEB will most likely be a choice in the intercity segment.

While renewable gas (biomethane) effectively contributes to GHG reduction, fossil based CNG is worse for climate than diesel [8] as it increases GHG emissions by 11%. This excludes impact of methane leaks—significant contributor to climate change. The choice of bus technologies is a multi-criteria decision problem summarised in Fig. 5.

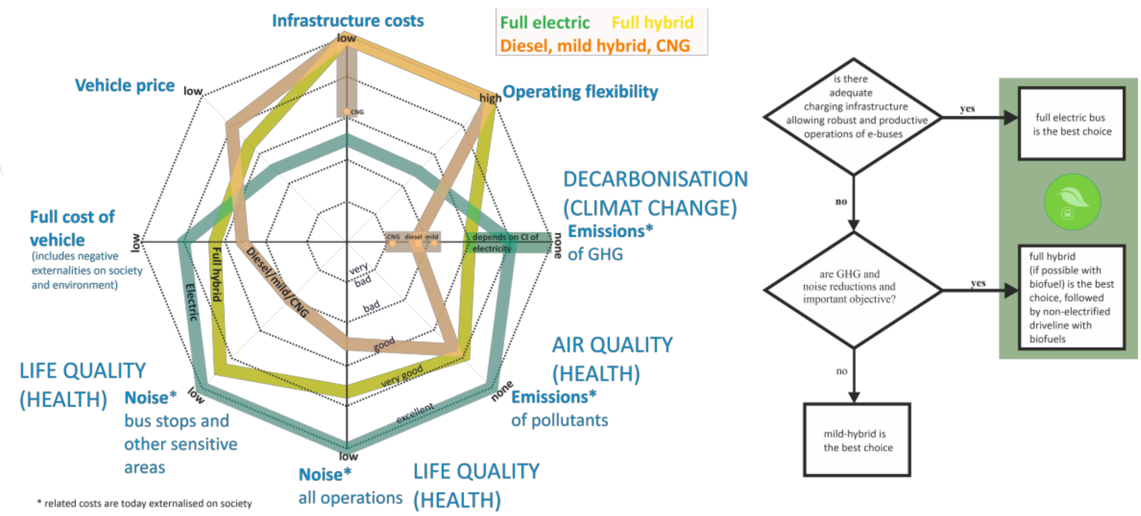

Figure 5 Multi-criteria view of bus technologies

In certain conditions electrified buses deliver higher GHG reductions than reported above. For instance, in hilly routes energy recovery is much above the average, allowing for instance full hybrids to drive in electric 30 to 50% of the route and reduce GHG by around 40%.

3. Bus connectivity and automation

Electrification plays a key role in making buses more attractive. However, it will not decarbonise PT alone. It needs to be part of a holistic strategy as environmental impact of a PT system is determined by its patronage. For instance, diesel buses operating in a city with well-designed and prioritised network (with high patronage) will be better for the environment/society than e-buses operating in a city with poorly designed network and non-prioritised operations where buses are trapped in mixed traffic (resulting in poor patronage). Switzerland is an example of a country where PT is competitive alternative to private cars. For instance, city of Bern has an outstanding system approach combining high-frequency service with dedicated lanes and signal priority. Percentage of full stops made at bus stops is one of the measures showing the degree of PT prioritisation in traffic. While typical values are in the 30-60% range, in Bern it is 80%, meaning that only two out of ten stops made by buses are the inefficient ones (stops at traffic jams or traffic signals).

There are several modifications that can be applied to the bus trajectory to reduce energy consumption and emissions. Each PT line runs according to a fixed schedule (timetables or headways), which determines its commercial speed. To increase on-time performance buses have slack time inserted in the schedule. It can slow down operations in certain situations and its amount is negatively correlated with the degree of priority of a route. It gives however certain flexibility in adjusting speed and dwell times. Fig. 6a shows typical relation between the average speed and energy consumption (full hybrid bus example). Routes with higher speed normally result in lower energy consumption, as average speed of a city bus is negatively correlated with the number of stops made by the bus (more stops mean more energy-costly accelerations).

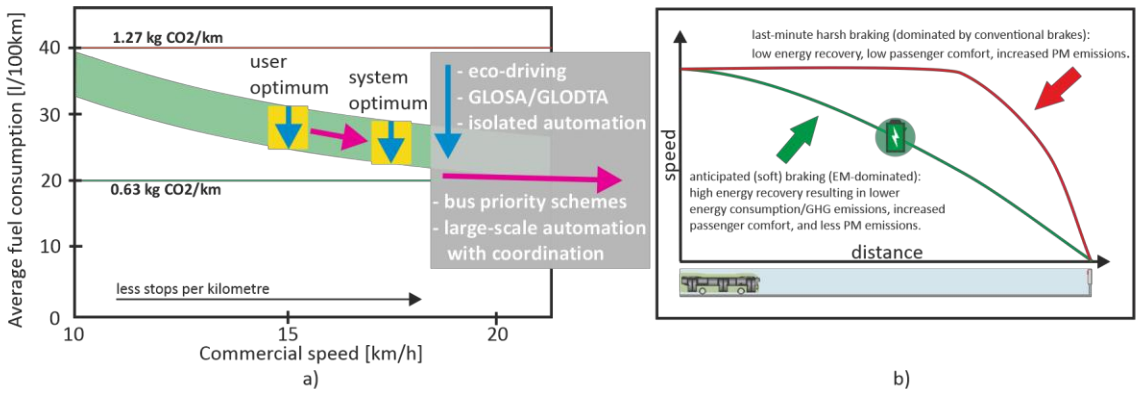

Figure 6 Energy consumption of a full hybrid bus (a), energy recovery via anticipated braking (b).

Driving style has significant impact on energy consumption. Fuel-efficient (eco-driving) strategy requires anticipation of what is happening ahead to minimise the number of accelerations and braking events [9]. It also improves passenger comfort. As eco-driving can reduce energy consumption and emission by on average 10%, it is an overlooked climate-change initiative [10]. With electrified buses there is an additional benefit of anticipative speed adjustment. Regenerative braking (enabled by high-power EM) recovers kinetic energy that would be otherwise lost into heat and converts it into electricity (typically up to 70% of energy that would normally be lost can be recovered). Smooth braking common with anticipative driving reduces usage of service brakes, hence, not only increases energy recovery but also reduces emissions of particulate matter from braking pads (Fig.6b). Existing traffic-management ITS applications have shown reductions in the order of 5% to 15% [11]. They have enormous potentials to support eco-driving via advanced driver assistance systems (ADAS). Following energy-efficient speed profiles can be supported by green light optimal speed advisory (GLOSA) extended with green light optimal dwell time advisory GLODTA, introduced in [12]. Example is given in Fig. 7.

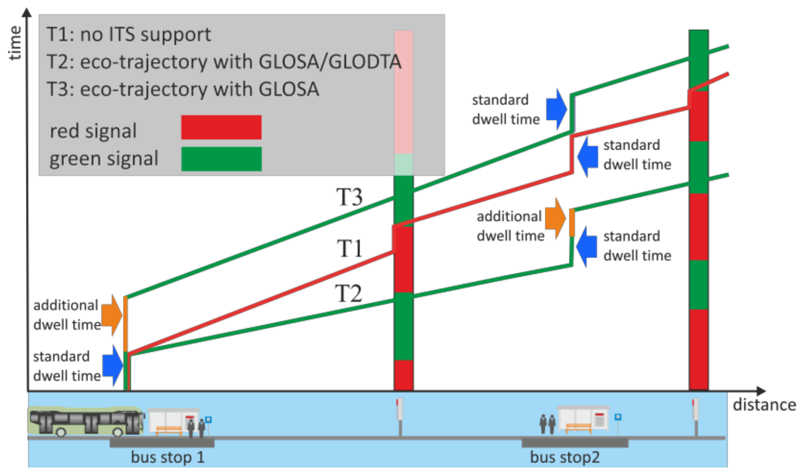

Figure 7 Eco trajectories supported by GLOSA/GLODTA.

They require connectivity and access to signal phase and timing (SPaT) [13]. Their goal is to provide advisories allowing to pass the upcoming traffic lights during a green interval. COSMO project showed that when bus drivers follow half of the speed recommendations a 20% reduction in fuel consumption is achieved [14]. However, without semi-autonomous execution support of the advisories, effectiveness of GLOSA/GLODTA systems in PT operations is limited. These systems can also minimise the negative side-effects on general traffic of conventional ITS such as transit signal priority systems (TSP). TSP adjusts traffic signal timing upon detection of an approaching bus (e.g. holding green lights longer) [15]. However, as TSP works at the expense of general traffic its acceptance at coordinated traffic systems is limited. Therefore, cooperative ADAS combining GLOSA, GLODTA and TSP [5] will be an essential element of the next-generation PT systems. It will allow increasing commercial speed of buses, supporting their on-time performance, and improving ride comfort, with minimum possible negative impact on private vehicle flows. Consequently, not only PT service quality level could be increased, but also energy consumption as well as emissions reduced. In the long term, automation combined with vehicle-to-everything (V2X) connectivity and information sharing will enable vehicles to coordinate their actions and execute optimal GLOSA/GLODTA strategies. Cooperative automation will further improve mobility system efficiency moving it towards system optimum and will allow to mitigate traffic paradoxes as flash crowd effect [16]. However, this requires additional control measures such as congestion pricing for private cars as preliminary analysis on the impact of automated vehicles on travel demand suggests 5% increase [11]. Future introduction of high-capacity/high-speed autonomous buses also raises questions about passenger acceptance. Experiments carried out in Luxembourg within the Horizon 2020 project PAsCAL [17] indicate that missing presence of driver on-board of a bus can be an issue to some passengers due to lack of assistance normally provided in various situations by drivers. Such assistance can be however partially replaced by new “digital” forms. While driving safety will increase with CAVs, crime-related safety perception will most likely decrease. The experiments also confirmed that while environment- and comfort-related benefits associated with autonomous buses are an important factor towards acceptance, PT CAV need to be fast to be an attractive alternative to private car. This cannot be achieved without dedicated lanes and ITS assistance (signal priority etc.).

4. Enhancing full hybrid buses with connectivity and geofencing

Full hybrid buses exploit the environmental- (GHG) and passenger-oriented (noise) potentials of electrification to the level that does not impose operating constraints on the operations (battery charging from the grid). They entered the market over ten years ago. The latest generation vehicles are reliable and have much better environmental and economic performance when compared with initial models. While being part-time electric they provide unconstrained productivity, thus are a bridge technology, especially in high mileage operations. The strategies for applying EM in a typical parallel full hybrid bus are shown in Fig. 8. In a conventional bus a decision how to use EM (power assistance to diesel engine vs. pure electric drive) is made by the vehicle itself. Pure electric drive typically is limited to takeoffs until around 20 km/h. Geofencing allows to add additional externally defined locations for electric drive. The use of geofencing technology to control electric drive (often referred to as zero emission zones) was pioneered by Volvo Buses in 2014 with plug in hybrids. Full hybrid buses started to use it only very recently [18-22]. Although the technical concept is the same, the application of the zones differs because full hybrids unlike plug-ins do not charge battery from the grid.

Hence, they have very limited electric energy budget, that depends on the energy recovery profile of a route. The "e-tailoring" concept [23] defines a special kind of zero emission zone referred to as an environmental zone. It is a segment of a route where driving in electric mode is not only technically possible (sufficient SoC, etc.) by a full hybrid bus, but will also reduce energy consumption/GHG emissions. Therefore, to optimise the use of electric energy, operating conditions of each line need to digitalised and next analysed to determine locations of environmental zones. This takes advantage of the fact that PT vehicles drive on a limited number of pre-defined routes.

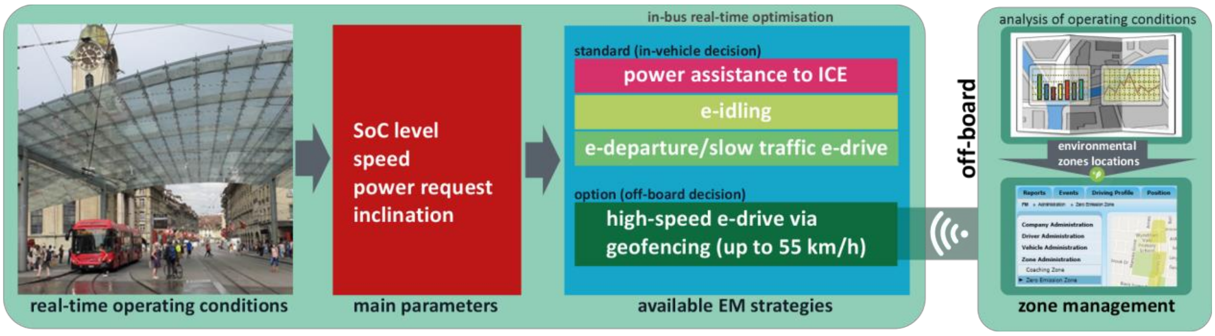

Figure 8 Applications of electric machine by full hybrid buses.

The concept has already been implemented in over 20 cities in the EU and Australia, with electric distance being on average doubled (typically to 20-30% share of a route), while energy and GHG emissions further reduced by 4%. However, in certain conditions (e.g. low operating speed combined with flat topography) zones are not possible as there is no excess energy. That is, all recovered energy is consumed by electric departure, meaning that default EM application strategy is the optimum one.

Below, we provide an example of operations in Sierre (Switzerland), which is world's first city, where its hybrid fleet was e-tailored to all city lines via geofencing [21]. The vehicle is a 12m full hybrid bus with a parallel hybrid system, 4-cylinder diesel engine (240hp), and EM rated at 120kW/800NM. Two operational periods were analysed. The first one was from 01.12.2019 to 01.02.2020, with standard behaviour. The second was between 01.12.2020 and 01.02.2021 with vehicle enhanced via geofencing. In the second period 22 zones were set in all lines in Sierre. Results are compared in Table 1.

Table 1 Results - performance comparison between period 1 and period 2.

	without geofencing (period 1)	with geofencing (period 2)
Electric distance [% of the route]	10	28
Electric time [%]	34	50
Electric time driving [%]	8	23
Electric time idling [%]	26	27
Fuel consumption [l/100km]	33	27
Average speed [km/h]	16	15
Number of stops per km	1.43	1.46
WTW CO2 emissions [kg CO2/km]	1.05	0.86
WTW CO2 emissions [tons], 70000km/bus	73.5	60

Thanks to environmental zones, electric distance share was nearly tripled, while electric time increased by 47%. Fuel consumption was reduced by 18%. Assuming yearly milage of 70000 km, e-tailored driving results in reduction of 13 tons of CO2. However, one must note that in the two period of operations conditions were not exactly same, mainly to variations in passenger loads (due to COVID-19). Nevertheless, conservative estimation of energy/emissions reduction is at least 10%, which translates to savings equal to 2300 litres of fuel and 7 tons of CO2 (in addition to original reductions via full hybrid technology). In the final e-tailoring zone setup, the average electric distance was increased to around 30%. When looking at specific routes, it ranges from 22% (the flattest one) to 50% (the most ones with most inclinations).

The e-tailoring benefits in Sierre are above the average due to hilly topography resulting in very high recovered energy surplus. Nevertheless, it illustrates significant potentials of connectivity and geofencing in improving economic, societal, and environmental benefits of the full hybrid technology.

Summary

Only attractive PT systems resulting in high patronage can deliver significant GHG emissions reductions from urban mobility. The reductions can be direct via introduction of clean vehicles, and most importantly, indirect, via modal shift from cars to PT if citizens find PT an attractive alternative. When it comes to clean (zero/low emission) vehicles there are only two mainstream choices—battery electrics (by far the best choice but with operating constraints) and part-time electric buses delivered by full hybrid technology. Biofuels such as biomethane or HVO also offer significant reductions, but their availability is limited. Electric buses (and to some extent full hybrids) also contribute to indirect GHG reductions. Since they deliver quieter operations and reduced tailpipe emissions, they make PT travel more attractive. However, passenger-friendlier buses are necessary but not sufficient condition to make PT an attractive choice. It is also about service quality that depends on several aspects such as network design, service frequency, on-time performance, and journey times. Future technologies applied to PT—C-ITS and automation—will have positive environmental and societal impact as they will increase passenger comfort, reduce emissions, and energy consumption. However, in parallel, the new technologies will also increase the efficiency and attractiveness of private cars. This means that without reclaiming road space and traffic signals for public transport, optimal decisions taken by citizens might not equate to the best collective outcome.

Acknowledgment

This work has been partially founded by the European Union's Horizon 2020 research and innovation programme under grant agreement number 815098 (PAsCAL project).

References

1. https://www.c40knowledgehub.org/s/article/How-to-make-public-transport-an-attractive-option-in-your-city?language=en_US
2. D. Andersson, R. Linscott, J. Nässén, Estimating car use rebound effects from Swedish microdata, Energy Efficiency, vol. 12, no. 8, pp. 2215–2225, 2019
3. Full free fare public transport: Objectives and alternatives, UITP Policy Brief, 2020

4. M. Gustafsson, et. al. Well-to-wheel climate performance of gas and electric vehicles in Europe, Transportation Research Part D, Elsevier, vol 97, 2021
5. M. Seredynski, G. Laskaris, F. Viti, Analysis of Cooperative Bus Priority at Traffic Signals, IEEE Transactions on Intelligent Transportation Systems, vol. 21, no. 5, pp. 1929–1940, 2020
6. Why full hybrids are the next-best alternative to electric buses https://www.volvobuses.com/en/news-stories/insights/understanding-the-latest-full-hybrid-technology.html?fbclid=IwAR10wz_J-VkEGexZRLvXPmriP9beoYvng2DULO0cnDGOkWqF-CRIF8gS1Ww
7. C. Fiori, et. al., Microscopic energy consumption modelling of electric buses: model development, calibration, and validation, Transportation Research Part D, Elsevier, vol 98, 2021
8. https://www.transportenvironment.org/news/spanish-court-ruling-confirms-%E2%80%98clean%E2%80%99-gas-vehicles-are-myth
9. M. Kamal, et. al., "On board eco-driving system for varying road-traffic environments using model predictive control", Proc. IEEE International Conference on Control Applications, 2010
10. J. Barkenbus, Eco-driving: An overlooked climate change initiative, Energy Policy, vol 38, 2010
11. M. Barth, G. Wu, and K. Boriboonsomsin, "Intelligent Transportation Systems for Improving Traffic Energy Efficiency and Reducing GHG from Roadways", policy brief, 2016
12. M. Seredynski et. al., "Complementing transit signal priority with speed and dwell time extension advisories," in Proc. 17th International IEEE Conference on ITS, 2014
13. M. Seredynski et. al., "Signal Phase and Timing (SPaT) for Cooperative Public Transport Priority Measures," Proc. 22nd ITS World Congress, 2015
14. "Sustainability report 2013, rethinking transportation, smarter solutions," Tech. Rep. 27, 2013
15. R. Wenming, et. al., A Transit Signal Priority Strategy With Right-Turn Lane Sharing, IEEE Access, vol 8, pp. 6238 - 6248, 2020
16. A. Grzybek, et. al., Mitigating flash crowd effect using connected vehicle technology, Vehicular Communications, vol. 2, pp 238-250, 2015
17. PAsCAL Horizon 2020 project, https://www.pascal-project.eu/
18. https://cdcvictoria.com.au/latest-news/cdc-hybrid-buses-zone-in-on-zero-emissions-on-melbourne-streets/
19. https://www.greencarcongress.com/2019/10/20191017-muni.html
20. http://www.transportengineer.org.uk/transport-engineer-features/tech-talk-focus-on-hybrid-buses-for-low-emission-zones/220839
21. https://www.volvobuses.com/en/news/2021/july/Swiss-city-first-to-connect-its-full-hybrid-fleet.html
22. https://www.volvobuses.com/en/news/2021/jan/luxembourg-takes-hybrid-technology-to-new-levels.html
23. M. Seredynski, Erik Lauri, and Hossein Zakizadeh, "Achieving significant economic and environmental benefits via ITS", Virtual ITS European Congress, 2020