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Energy consumption and cost-benefit analysis of hybrid and electric city buses

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ABSTRACT

This paper presents a cost-benefit analysis (CBA) of hybrid and electric city buses in fleet operation. The analysis is founded on an energy consumption analysis, which is carried out on the basis of extensive simulations in different bus routes. A conventional diesel city bus is used as a reference for the CBA. Five different full size hybrid and electric city bus configurations were considered in this study; two parallel and two series hybrid buses, and one electric city bus. Overall, the simulation results indicate that plug-in hybrid and electric city buses have the best potential to reduce energy consumption and emissions. The capital and energy storage system costs of city buses are the most critical factors for improving the cost-efficiency of these alternative city bus configurations. Furthermore, the operation schedule and route planning are important to take into account when selecting hybrid and electric city buses for fleet operation.

1. Introduction

Increasing environmental concerns and unstable fuel prices have made hybrid vehicles (HEVs) and battery electric vehicles (BEVs) more and more interesting as viable replacements to conventional vehicles. These types of vehicles have already been available on the passenger car and heavy vehicle markets for more than ten years. Therefore, viability of the related powertrain technology has already been proven and acceptance by customers has been attained. Despite of the technological success, life cycle costs of the HEVs and BEVs are still, in most cases, higher than the costs of the conventional vehicles (Nylund and Koponen, 2012; van Vliet et al., 2010).

Most of the life cycle costs of city buses come from the capital and operating costs (Nylund and Koponen, 2012; Clark et al., 2008). Even though the capital costs of hybrid and electric city buses are high, the lower energy consumption significantly reduces the operating costs what makes them already potential replacements for the conventional diesel city buses (Feng and Figliozzi, 2013; Hellgren, 2007). The diversification in alternative powertrain technology increases the challenges in decision making that is why it is necessary to study in great detail the different configurations of city buses. This is especially important in the estimation of the cost-efficiency of city buses when the operation schedule and route planning are taken into account.

Lot of research has been made for demonstrating the potential of hybrid buses to improve the energy efficiency and to reduce emissions. Most of the research has been focused on topology comparisons (Katrašnik et al., 2007; Williamson et al., 2006), particular applications (Bubna et al., 2010, 2012), or developing the energy management strategy (Suh et al., 2012; Xu et al., 2012). Recently, techno-economic analysis has been a subject of interest especially for passenger vehicles (Sharma et al., 2012; Weiss et al., 2012; Offer et al., 2010; van Vliet et al., 2010), and in some extent also for city buses (Croft

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McKenzie and Durango-Cohen, 2012; Nylund and Koponen, 2012). Relatively lot of research has been carried out for fuel cell hybrid buses e.g. (Xu et al., 2012; Bubna et al., 2010; Ally and Pryor, 2009; Saxe et al., 2008) despite of the fact that fuel cells are still expensive, they require a dedicated infrastructure, and their durability is not fully confirmed in vehicle use (Ahluwalia et al., 2012; Wang et al., 2011). For example, in a recent study the fuel cell bus was estimated about twice more expensive than a battery electric city bus (Bubna et al., 2010).

There are only few research papers which present an exhaustive cost-benefit analysis of city buses e.g. (Croft McKenzie and Durango-Cohen, 2012; Hellgren, 2007). Some informative reports have been written about this subject (Nylund and Koponen, 2012; Clark et al., 2008) where the life cycle costs of the different types of city buses have been compared. However, there are no comprehensive studies made where different alternatives of city buses and different types of bus operation would have been taken into account. Typically, the presented cost-benefit analyses have included conventional diesel and diesel hybrid buses. Plug-in hybrid buses have not been considered probably because there are not many commercial buses available. Also, the cost-efficiency of full electric buses has not been thoroughly analyzed with the latest energy storage technology in the literature even though electric buses offer a lot of potential especially in saving energy. This research presents an energy consumption and cost-benefit analysis of different hybrid and electric city bus configurations. An extensive energy consumption analysis is carried out on the basis of simulation results. Vehicle simulation was used as the research method because it is fast and relatively accurate way of defining the performance and energy efficiency of the current and future technologies. The cost-efficiency is defined through a calculation where fleet operation in different types of operation routes is taken into account. This way the comparison to currently dominant conventional diesel city buses can be fairly done. The analysis includes two parallel hybrids (one with ultracapacitors and one with batteries as energy storage), a series hybrid, a plug-in series hybrid, and an electric city bus. Fuel cell powered city buses were excluded from this analysis due to their lack of market maturity in terms of capital costs and fuel infrastructure (Ahluwalia et al., 2012).

2. Hybrid and electric city buses

2.1. Hybridization and electric power trains

By definition, hybrid and electric vehicles have lots of potential to achieve lower energy consumption than conventional vehicles (Banjac et al., 2009; Katrašnik et al., 2007; Åhman, 2001). In the case of heavy vehicles, most of the hybrid and electric powertrain applications have been developed for city buses. This is an obvious application because the typical use of city buses is extremely well suited to make the best use of many benefits of the electric powertrain and hybrid technology (Bubna et al., 2010; Williamson et al., 2006). In fact, feasible designs for electric and hybrid city buses have been already done a long time ago (Hoffman, 1972; Parsegian, 1969). The biggest technological barrier has been the energy storage but nowadays lithium-ion batteries offer an adequate performance in terms of the power and energy capacity (Burke and Miller, 2011; Scrosati and Garche, 2010). However, the costs of the lithium based batteries are quite high but there is strong believe that these costs can be significantly reduced in the future (Santini et al., 2010). When compared to passenger cars, the amount of energy used by city buses in their lifetime is a lot more, which makes it even more attractive to use electric powertrains and hybrid systems in city buses. Hybridization is not automatically beneficial for regulated emissions because they depend heavily on the engine operation point and the driving cycle. Moreover, there is always a compromise solution to be done between the emissions and fuel economy (Nylund and Koponen, 2012). In addition to improved powertrain efficiency, electrification allows for eliminating idle losses in auxiliary devices and enhancing their energy efficiency (Campbell et al., 2012).

2.2. Hybrid bus topologies

Currently, most of the commercially available hybrid transit city buses have a series hybrid powertrain topology. The series topology is probably the easiest solution to hybridize a city bus (Ehsani et al., 2010). This is because all the traction power is produced only by an electric motor or by several electric motors and the engine-generator (gen-set), with energy storage, provides the power for the traction. As there is no mechanical link between the engine and the wheels, placement of the components is quite flexible and the engine control is not dependent on the vehicle's speed. In addition, the optimization of the energy management can be practically done on the basis of the gen-set use for the driving power and recharge power needs of the energy storage. Fig. 1 presents the simplified layouts for the configurations of the conventional, hybrid and electric powertrains.

A parallel hybrid topology has its own advantages. The degree of hybridization can vary quite a lot which allows fitting the hybrid configuration to the given application and operation. As the engine is directly linked to the wheels, it results in a higher efficiency powertrain than the series topology (Katrašnik et al., 2007). By integrating the electric traction motor in the transmission, the hybrid powertrain can be fit in a quite compact volume and practically replace the conventional automatic transmission. A parallel hybrid usually has either a battery pack or ultracapacitors (Rotenberg et al., 2011) as electrical energy storage. Ultracapacitors provide a high power but low energy solution but it is well suitable for stop-and-go type of driving. Typically, the parallel hybrid powertrain is more energy efficient in higher average speed driving and the series hybrid achieve higher energy efficiency in lower average speeds (Muncrief et al., 2012). Although, many variables, such as driving cycle, operating conditions and auxiliary power, impact on the energy efficiency (Muncrief et al., 2012; Suh et al., 2012).

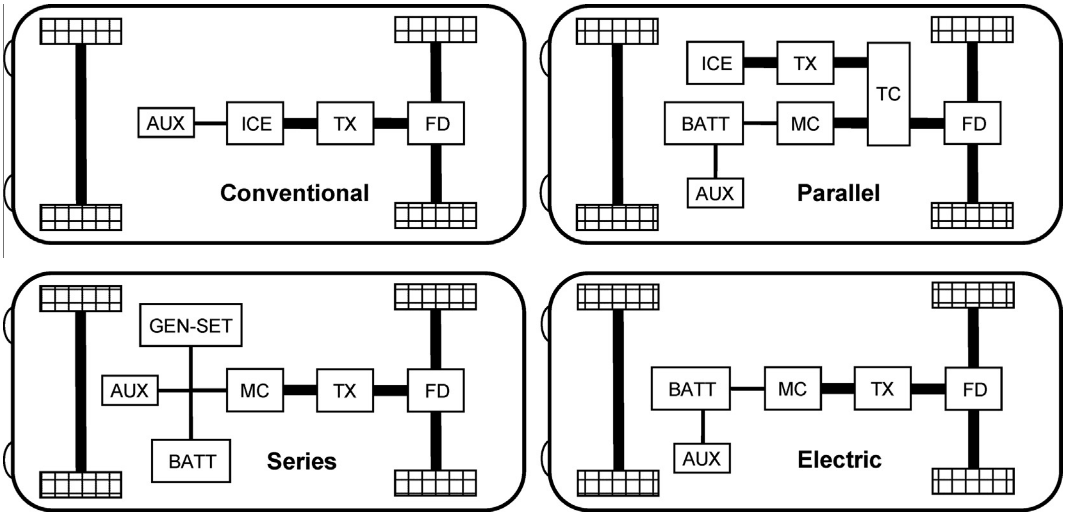

Fig. 1. Simplified layouts of the different city bus configurations (ICE = diesel engine, TX = transmission, FD = final drive, AUX = auxiliary devices, TC = torque coupler, MC = motor/controller, BATT = battery, GEN-SET = engine-generator).

2.3. Electric city buses

Full size electric city buses became recently commercially available. The recent developments in battery technology have increased the potential of electric buses to be viable solution for mass public transport (Choi et al., 2012; Festner and Karbowski, 2012; Brecher, 2010). The potential of battery electric city buses for energy savings and reduction of emissions has been noticed a long time ago as well as the possible technological solutions (Hoffman, 1972). There are several possible topologies for full electric powertrain (Lajunen, 2012b; Ehsani et al., 2010) which allows to design the powertrain to be best suitable for a given application and operation. However, the battery technology has not been mature enough in terms of durability, costs and energy density for a breakthrough of large scale commercialization of electric city buses. With lithium-ion batteries, full electric vehicles are more competitive than before (Scrosati and Garche, 2010) even though the technology is still developing and relatively expensive. The operation range remains a challenge for passenger vehicles but for electric city buses it may not be as problematic if the operation of buses is well managed in terms of charging and route planning (Offer et al., 2010). In difference to diesel and charge sustaining hybrid buses, the plug-in hybrid and electric buses require a dedicated charging equipment and infrastructure for their operation. This increases the initial costs, but because this kind of infrastructure can be used much longer time than the buses the eventual costs impact on the life cycle cost of the bus fleet operation is not that significant.

2.4. Cost comparison

Hybrid and electric buses are more expensive to manufacture than conventional diesel buses (Ahluwalia et al., 2012; Feng and Figliozzi, 2012; Williamson, 2012; Clark et al., 2007). Most of the extra costs consist of the expensive electric components, such as battery, electric motor and power electronics, and the engineering development work especially on the system management. Because most of the electric components require relatively steady operation conditions, liquid cooling is often used to manage the thermal balance which requires additional subsystems and control management. The electric auxiliary devices can increase the energy efficiency, but as the market of these components is still small, their costs are quite high (Campbell et al., 2012). There is no significant difference in the capital costs between a parallel and series hybrid buses. The parallel hybrid can be less expensive due to the lower hybridization rate, thus the electric components have lower power ratings. In addition, the energy storage size in parallel hybrid buses can be small especially in the power-assist type of hybrids. On the contrary, the full electric city bus is much more expensive than the hybrid buses because of the large size batteries. The plug-in hybrid capital costs are obviously highly dependent on the size of the on-board battery. The series hybrid maintenance cost can be lower due to less stresses for the engine but the additional components makes it equal compared to parallel hybrid (van Vliet et al., 2010). The maintenance costs for electric buses could be lot less than for a conventional diesel bus (Feng and Figliozzi, 2013).

There is a lot of uncertainty in the estimations of alternative powertrain costs (Feng and Figliozzi, 2013; van Vliet et al., 2010). As these vehicles have not been manufactured in large volume series, precise costs are difficult to estimate. Price forecasts were estimated by technology learning rate by Weiss et al. (2012) and the result showed that it is hard to estimate technological development of HEVs and BEVs in terms of costs as their production is not mature enough when compared to conventional cars. It was also stated by Weiss et al. (2012) that the cost performance of batteries is critical to hybrid and electric vehicles. In the published results, there is a large variation about the cost-efficiency of hybrid and electric city buses. Depending on the initial parameters of analysis, hybrid city buses can already have lower life cycle costs than their diesel counterparts as it is presented by Hellgren (2007). As there are no fixed price lists available for city buses, estimations for the capital costs, especially for the hybrid and electric buses, have large variation. Table 1 shows a summary of the diesel and hybrid bus purchase costs presented in the literature.

Based on the literature (Table 1), diesel hybrid city buses are estimated around 30–70% more expensive. The large variation can be partly explained by the different hybrid technologies. (Ahluwalia et al., 2012; Croft McKenzie and Durango-Cohen, 2012; Nylund and Koponen, 2012; Bubna et al., 2010; Clark et al., 2008]. There are not a lot of estimations presented for the costs of full electric buses but it is assumed that they could be at least twice more expensive than diesel buses (Ahluwalia et al., 2012). In the operation of city buses, the local policies and energy costs also have an important role for the cost efficiency. Especially, differences in the taxation policies of the energy in different countries make the overall cost calculation quite difficult.

3. Characteristics of energy storages

3.1. Life cycle

The energy storage, typically a battery or ultracapacitors, including its management system is the most important component for the hybrid and electric buses in terms of technical durability and costs (Wood et al., 2011; Lodi et al., 2010; Kellaway, 2007). The battery technologies are under development but especially the lithium-ion technology shows already promising characteristics concerning energy and power density (Burke and Miller, 2011). Estimations for durability of lithium-ion batteries in city buses are somewhat hard to make because the operating conditions can vary a great deal in terms of the discharge and charge current demand, and temperature. Battery manufacturers typically define the life cycle performance in deep discharge-charge cycles in constant and low current rate conditions which may not correspond very well to the real operating conditions. For ultracapacitors, the life cycle is not as problematic but because their energy capacity is low comparing to batteries (Burke and Miller, 2011), they are only suitable for mild hybrid solutions or supporting a battery in a dual-source energy storage system (Bubna et al., 2012).

3.2. Costs

In a very recent study (Bubna et al., 2012) the market prices of the lithium-titanate batteries and ultracapacitors suitable for vehicular application were presented. According to that study, the battery cost would be around 1250€/kW h and for ultracapacitors 35000€/kW h. If the cost of the ultracapacitors is expressed as per power unit, the cost is much more reasonable being about 90€/kW. Similar prices for energy storages have been presented also in some other publications. However, there is reason to believe that the cost of batteries will notably decrease in the future (Santini et al., 2010). It is not yet exactly clear how the cost between the numerous lithium based chemistries will evolve but some of the chemistries are considered more promising than the others depending on the given application (Lajunen, 2012a; Lajunen and Suomela, 2012). Among the lithium-ion battery chemistries, there is a division to high-power and high-energy battery chemistries. High power batteries are more suitable for charge-sustaining hybrid powertrains and high energy batteries for plug-in and full electric powertrains.

Table 1
Summary of the purchase costs of diesel and hybrid buses.

Reference	Year	Diesel bus cost	Hybrid bus cost	Data source
Lastauto Omnibus (2013)	2013	222,000€		Mercedes Integro Euro 6
Ahluwalia et al. (2012)	2012	$325,000	$550,000	The data are from a cost analysis by BAE Systems
Feng and Figliozzi (2013)	2012	$368,500	$479,000	New Flyer 60ft diesel and diesel-hybrid buses
Lastauto Omnibus (2012a)	2012		360,000€	MAN Lion's City Hybrid (series hybrid with ultracapacitors) (MAN, 2013)
Nylund and Koponen (2012)	2012	215,000€	330,000€	Cost are estimated
Williamson (2012)	2012	380,000€[a]	488 000€[a]	Diesel bus is Volvo B12 and hybrid bus a series hybrid technology developed by BAE Systems
Zaetta and Madden (2011)	2011	170,000€–250,000€	350,000€	No data source declared
Hallmark et al. (2012)	2010	$367,000	$522,000	Bus specifications from Gillig (parallel hybrid)
Croft McKenzie and Durango-Cohen (2012)	2008	$347,000	$460,000	The data are from National Renewable Energy Laboratory transit bus demonstration projects
Laver et al. (2007)	2007	$350,000	$500,000	Typical purchase costs for 40-foot buses
Clark et al. (2007)	2006	$319,700	$531,600	Costs are the average prices calculated from the 2006 Transit Vehicle Database
Foyt (2005)	2005	$320,000	$500,000	The data were provided by CTTransit
Barnitt (2008)	2004		$385,000	Actual costs at the time of purchase (BAE Systems HybriDrive Gen II)

[a] Original costs are in Australian dollars, an exchange rate of 0.8 was applied.

The high power batteries are more expensive but usually their required size as a battery pack is quite small, therefore the total costs are not that high. The high energy batteries profit from the fact that a larger cell has cheaper manufacturing costs as it was noted by Santini et al. (2010). At the moment, there are numerous estimations about the battery costs and it is not easy to define a list price for any lithium-ion battery chemistry, or estimate accurately the future prices.

3.3. Dimensioning

The energy storage system (ESS) has an important impact on the total energy efficiency of the city bus and also on the capital costs. Therefore, the size and properties of the ESS should be well suitable to the corresponding use of the bus in order to make good use of the ESS. There are several ways to dimension the energy storage depending on the design targets (Ravey et al., 2011; Kellaway, 2007). In this research, the energy storages were dimensioned on the basis of the existing solutions in commercial city buses e.g. ultracapacitors (MAN, 2013; Lastauto Omnibus, 2012a) and batteries (Ebusco, 2013; Lastauto Omnibus, 2012b). Commercially available lithium batteries and ultracapacitors were used as reference in defining the ESS parameters for the simulation models and for the cost calculations (Maxwell, 2013; Saft, 2013). Because precise battery life cycle is hard to estimate or there is no available data to do it, in this study the battery life is calculated based on the total energy throughput of the battery and the manufacturer's data on the cycle life.

4. Calculation of the bus operation

4.1. Fleet operation

The cost-benefit analysis was conducted for a bus fleet for being able to equally compare the different bus applications in terms of life cycle costs. The calculation of the bus fleet is presented in Eqs. (1)–(6). The required numbers of conventional and hybrid buses for fleet operation were defined with Eq. (1).

$$N_C \approx N_{min} = \frac{t_r}{t_{int}}, \quad \text{where } N_C \in N = \{1, 2, 3 \ldots N\} \tag{1}$$

where N_C is the required number of buses (integer), N_{min} is the minimum required number of buses (mathematical), t_r is the duration of the bus route and t_{int} is the operation interval. The waiting time (t_w) before the operation of an individual bus is

$$t_w = N_C t_{int} - t_r \tag{2}$$

The total duration of the route including waiting time (t_{rtot}) is calculated with the aid of the minimum waiting time (t_{lim}). The final number of buses is then calculated with the t_{rtot} instead of t_r as shown in Eq. (3). The minimum waiting time was defined to be 5 min.

$$t_{rtot} = t_r + t_w, \quad \text{if } t_w < t_{lim} \Rightarrow t_{rtot} = t_r + t_{lim} \Rightarrow N_C = \frac{t_{rtot}}{t_{int}} \tag{3}$$

The charging of the plug-in hybrid bus was assumed to be done during the waiting time before the operation. This could be considered as a fast charge operation which would need a powerful charging unit. Only for the electric bus the number of buses was different due to the time consuming battery charging. The required charging time (t_{chg}) for the electric bus is

$$t_{chg} = \frac{R_E E_{route}}{P_{chg}}, \quad \text{where } R_E \in R = \{1, 2, 3, \ldots R\} \tag{4}$$

where R_E is the operating range as a number of operation routes, E_{route} is the energy consumed for one route and P_{chg} is the external charging power of the battery. The maximum available time (t_a) to recharge an individual electric bus is then

$$t_a = \frac{R_E t_{rtot}}{N_C} \tag{5}$$

The required number of electric buses (N_E) for a fleet operation is then

$$N_E = N_C + \frac{t_{chg}}{t_a} = N_C \left(1 + \frac{E_{route}}{P_{chg} t_{rtot}}\right) \tag{6}$$

For the hybrid plug-in bus, two operation modes were defined: charge-depleting (CD), and charge-sustaining (CS) mode. For avoiding too much impact of the charging on the plug-in hybrid bus operation, the amount of charged energy was fixed for each route for better comparison between the different driving cycles. This amount of energy was enough to operate 75% of the route in CD mode and the rest in CS mode.

4.2. Operation routes

As there can be significant variations in the energy consumption depending on the driving pattern, six different types of city bus driving cycles were used for creating specific operation routes for simulations. Table 2 presents the characteristics of these cycles, which are route 550 (a Helsinki region bus line), BR (Braunschweig), H3 (Helsinki3 is an extra urban cycle), MAN (Manhattan bus cycle), NYC (New York Bus cycle) and OCC (Orange County Bus Cycle). The cycles BR, MAN, NYC and OCC are well-known dynamometer test cycles for heavy-duty vehicles and are often used for city buses to evaluate their energy efficiency. The data for these cycles is available in many sources e.g. (Dieselnet, 2013) and also in several vehicle simulation tools e.g. (Markel et al., 2002).

The route 550 is a measured driving cycle which corresponds to a bus line in Helsinki region in Finland. It is especially interesting because it has sub urban driving patterns mixed with typical urban driving. The cycle differs in demands of top speed and stops per driven distance compared to traditional reference cycles. The H3 cycle corresponds to extra urban driving being comparable a bus operation in an arterial road around a city center.

The specific bus routes were generated by including one or more cycles in one route. For comparison reasons, the routes were defined to be about the same length in duration. The descriptions of the routes are given in Table 3. Routes MAN and NYC have lower operating interval because of their inner city type of driving whereas extra urban cycle H3 has the highest operating interval. Fig. 2 presents all the routes in their entire length.

5. Simulation models

5.1. Simulation environment

ADVISOR vehicle simulation program was used as the simulation environment. The program is designed for rapid analysis of the performance and fuel economy of conventional and advanced, light and heavy-duty vehicle models as well as hybrid electric and fuel cell vehicle models (Markel et al., 2002; Wipke et al., 1999). ADVISOR has been widely used for defining the energy efficiency of vehicles with alternative powertrains e.g. (Suh et al., 2012). The simulation models of the conventional and hybrid buses used in this study are described in (Lajunen, 2012a) with their corresponding energy management strategies. The model of the electric city bus was developed during a study were different powertrain alternatives were compared (Lajunen, 2012b). The alternative with single permanent magnet electric traction motor with batteries as energy storage was chosen for this study as the electric bus configuration.

5.2. Configuration of simulation models

The common technical characteristics (Table 4) of all the simulation models are based on a full size (12 m), lightweight, diesel engine powered city bus with a 6 gear automatic transmission. The corresponding actual diesel bus is a lightweight city bus manufactured by a Finnish company Kabus Oy (Kabus, 2013).

The powertrain configurations of all bus models are presented in Tables 5 and 6. The configuration of main components of the hybrid and electric bus models was done in respect of the requirements of the chosen driving cycles as well as the specifications of commercially existing city buses in Europe e.g. (Ebusco, 2013; MAN, 2013; Lastauto Omnibus, 2012a, 2012b). As

Table 2
Characteristics of the driving cycles used in simulations.

Cycle	550	BR	H3	MAN	NYC	OCC
Max speed (km/h)	83.3	58.2	71.7	40.7	49.6	65.4
Average total speed (km/h)	31.5	22.5	41.2	11.0	5.9	19.8
Average speed (km/h)	35.9	30.1	48.4	17.2	18.1	25.2
Distance (km)	28.6	10.9	10.3	3.3	1.0	10.5
Stop time percentage (%)	13.3	25.7	15.2	35.1	61.5	20.7
Stops per km	1.4	2.6	0.8	5.7	10.1	2.9
Max acceleration (m/s^2)	1.8	2.4	1.4	2.1	2.8	1.8
Min acceleration (m/s^2)	−2.1	−3.6	−1.9	−2.5	−2.1	−2.3
Duration (s)	3276	1741	903	1090	601	1910

Table 3
Descriptions of the generated bus routes.

Route	550	BR	H3	MAN	NYC	OCC
Number of cycles	1	2	4	3	6	2
Duration (min)	54.6	58.0	60.2	54.5	60.1	63.7
Total distance (km)	28.6	21.7	41.3	10.0	5.9	21.0
Operation interval (min)	10	10	20	5	5	15

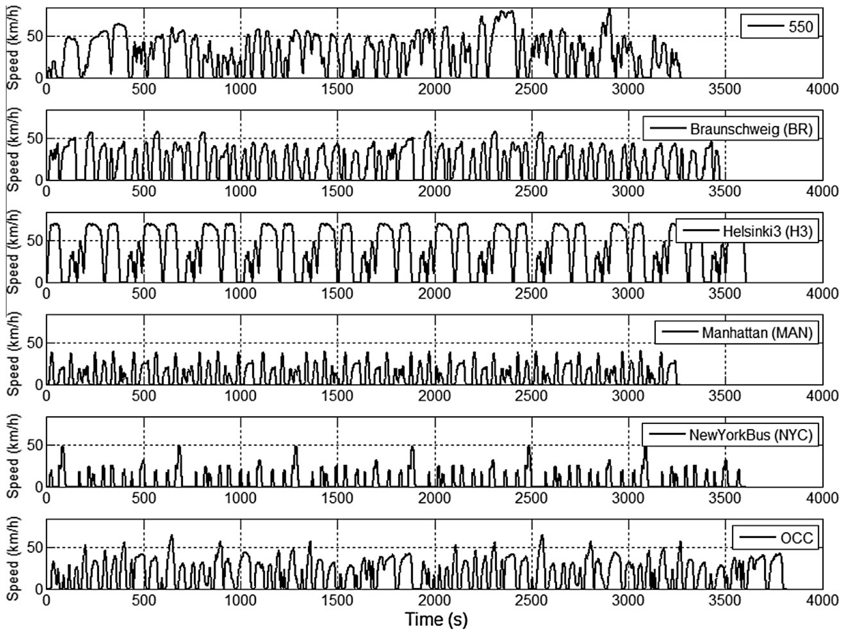

Fig. 2. Simulated operation routes.

Table 4
General characteristics of the simulation models.

Parameter	Value
Curb weight (kg)	10,000
Vehicle frontal area (m^2)	6.2
Drag coefficient	0.6
Rolling resistance	0.01
Wheelbase (m)	6.5
Front weight fraction	0.34
Centre of gravity, height (m)	1.0

Table 5
Conventional and parallel hybrid bus powertrain configurations.

	CONV	PAR_1	PAR_2
Engine power (kW)	202	162	140
Electric motor power (kW)	–	75	100
Battery configuration	–	–	Saft 6Ah cell, 2 packs in parallel, 144 cells in series in a pack
Battery system voltage (V)	–	–	518
Ultracapacitors	–	Maxwell BCAP3000, 280 capacitors in series	–
Energy storage weight (kg)	–	300	225
Transmission	6-speed Allison T280R gear ratios [3.49; 1.86; 1.41; 1.00; 0.75; 0.65]		

the chosen bus frame is lightweight, the power ratings of the electric motors and engines were chosen lower than that of the typical commercial city buses. Some of the city bus manufacturers are already offering lightweight buses and it is considered to be a growing trend in the future because of the positive impact on the energy efficiency. The bus models were configured also the way that the hybrid and electric bus models have at least the same performance as the reference diesel bus model.

Description of the different bus configurations

- CONV: A lightweight diesel city bus.
- PAR_1: A parallel hybrid bus with ultracapacitors as energy storage.
- PAR_2: A parallel hybrid bus with a high-power lithium-ion battery as energy storage.
- SER_1: A series hybrid bus with a high-power lithium-ion battery as energy storage.
- SER_2: A plug-in hybrid bus with a series hybrid powertrain and a high-energy lithium-ion battery as energy storage.
- EV: A full electric city bus with a high-energy lithium-ion battery as energy storage.

Table 6
Series hybrid and electric bus powertrain configurations.

	SER_1	SER_2	EV
Gen-set power (kW)	110	63	–
Electric motor power (kW)	150	150	150
Battery configuration	Saft 6Ah cell, 3 packs in parallel, 144 cells in series in a pack	Kokam 40Ah, 2 packs in parallel, 168 cells in series in a pack	Kokam 40Ah, 6 packs in parallel, 168 cells in series in a pack
Battery system voltage (V)	518	622	622
Battery nominal power (kW)	131	373	373
Battery capacity (kW h)	9.3	49.7	149
Energy storage weight (kg)	338	505	1514
Battery cycle life (cycles)	10,000	3000	3000

The parallel hybrids and SER_1 are charge-sustaining (CS) hybrid buses meaning that the net energy balance of the energy storage is about zero over any driving mission.

The final drive gear ratio in all models is 4.89. The batteries were chosen on the basis on the best suitability to the bus configuration. The charge sustaining parallel and series buses with batteries (PAR_2 and SER_2) require power type battery meaning that the battery has high P/E ratio (Santini et al., 2010). The batteries in the plug-in hybrid and electric bus are energy type batteries (electrode materials: $LiCoO_2$ and Carbon). There is no simple rule for the dimensioning the battery capacity for the plug-in hybrid and electric buses. In this case, the battery size for the plug-in hybrid was defined based on the maximum required energy consumption on the chosen operation routes. In the simulations, the plug-in operated 75% of the route in pure electric mode and 25% in hybrid mode. The electric operation share was kept constant for all the operating routes even if there could be a possibility to operate more time in pure electric mode. It is possible and presumable that the manufacturers of full electric buses will offer the possibility for the customers to choose the battery capacity (and battery type) depending on their needs in terms of bus operation.

The power consumption of the auxiliary devices in a city bus can vary largely depending on the operating conditions. The electrification and smart control of the auxiliary devices can reduce this power consumption as it is presented by Campbell et al. (2012) and Muncrief et al. (2012). In this study, each of the auxiliary devices was separately modeled to be able to take the impact of the auxiliary power into account in detail for each bus configuration. The auxiliary power consumption and analysis are presented in the simulation results (section 7).

The total weight of a bus in simulations consisted of curb weight of 10,000 kg, about 20 passengers (1500 kg) and the weight of the energy storage system. The chosen number of passengers is not based on any data but because buses are not operated empty, a certain number of passengers was chosen corresponding in this case about 25–30% of the full passenger capacity of a typical 12-m long city bus. This produces the weights between 11,500 and 13,000 kg from the diesel bus to the electric bus. It was considered that the different bus configuration would be about the same weight except the energy storage system which can be relatively heavy up to 10% of the total weight of the bus. The increased weight has not been considered to have any effect on the passenger capacity in this analysis. All simulations were conducted in 20 °C of ambient temperature. The energy storage system temperature was kept in between 20 and 25 °C with the aid of active cooling and the cooling power losses were taken into account in the simulations.

5.3. Data sources

Most of the model components were configured by using the ADVISOR component library. The diesel engine data for the conventional bus model was acquired from the measurements done in a laboratory test facility which allowed for creating realistic steady state engine and emission maps. The downsized engine versions of the hybrid buses were calculated from the measured engine. The data for the ultracapacitors and high-power battery were acquired from the manufacturers' datasheets (Maxwell, 2013; Saft, 2013). The high-energy battery data was acquired from a laboratory measurement (Lajunen, 2012a).

6. Cost-benefit analysis

6.1. Formulation

The cost-benefit analysis was carried out by calculating the life cycle costs for the different bus fleets in each operation route. The following variables were taken into account in the life cycle cost calculation; capital costs, operating costs, and costs of the energy storage system replacements. The capital costs consist of the purchase costs of the buses and charging equipment if needed. The operating costs include diesel and electricity consumption, and maintenance costs. The maintenance costs include general repairs and spare parts. The following assumptions were made for the cost-benefit analysis

- All the buses and required charging equipment for the fleets are purchased at the beginning of operation.
- The labor costs are not included to the calculation because it is assumed that they are equal for all different bus fleets.
- The discount rate is assumed to be 7% per year (Laver et al., 2007).
- The salvage value of all buses is considered to be zero at the end of their service life.
- The calculation of the life cycle costs does not take into account any random failures of the technology because it is out of the scope of this research.

It is considered here, that all the buses in the fleet are purchased at same time because this would be an expected scenario for a transit agency when choosing new powertrain technology for buses. No salvage value is considered in this study because after the expected service life of a city bus, the salvage value is considered to be very small, so that it basically does not have impact on the life cycle costs (Laver et al., 2007).

For defining the amount of required energy storage replacements during the service life of the buses, the energy storage life has to be calculated. This was defined on the basis of the total energy throughput. Eq. (7) defines the energy storage life (B_{life}) in kilometers of operation for a single bus.

$$B_{life} = \left(\frac{N_{cycle}E_{ess}}{E_{km}}\right)\left(\frac{N_B}{N_C}\right) \tag{7}$$

where N_{cycle} is the energy storage life as amount of deep discharge-charge cycles, E_{ess} is the energy capacity of the storage (kW h), E_{km} is the energy throughput in operation (kW h/km), N_B is the number of hybrid or electric buses used for the fleet operation, and N_C is the minimum required amount of buses for the fleet operation. The cycle life for the batteries was presented in Table 6, and for the ultracapacitors, a full discharge-charge cycle value of one million cycles was used as cycle life. The number of the energy storage replacements (N_{ess}) during the service life of a bus can be defined on the basis of the driven distance (D_{LC}).

$$N_{ess} = \frac{D_{LC}}{B_{life}}, \quad \text{where } N_{ess} \in N = \{1, 2, 3 \ldots N\} \tag{8}$$

The life cycle costs (C_{LC}) for a bus fleet was calculated by summing up the different costs

$$C_{LC} = N_{init}f_C C_{cag} + X_{chg}C_{chb} + \sum_{t=0}^{T}(N_{init}C_{op}D_a + N_t C_{ess}) \cdot (1 + d_{rate})^{-t} \tag{9}$$

where N_{init} is either N_C or N_B depending on the bus configuration, f_C is the cost factor of a hybrid or electric bus (for diesel bus $f_C = 1$), C_{cap} is the capital cost of a conventional diesel bus, X_{chg} is 1 for rechargeable buses and 0 for the other type of buses, and C_{chg} is the cost of the external charging equipment, C_{op} is the yearly operating cost (€/km), D_a is the yearly driven distance in operation, N_t is the number of energy storage replacement at year t, C_{ess} is the energy storage cost (either C_{batt_hp}, C_{batt_he} or C_{ucap}), d_{rate} is the discount rate, and t is the time periods. In this case, life cycle costs are calculated yearly basis then

$$t \in T = \{0, 1, 2, \ldots, T_s\}, \tag{10}$$

where T_s is the service life in years. The yearly operating cost are calculated with Eq. (11)

$$C_{op} = C_{fuel}F_{cons} + C_{elec}E_{cons} + C_{mc}, \tag{11}$$

where C_{fuel} is the diesel fuel costs (€/l), F_{cons} is the fuel consumption (l/km), C_{elec} is the electricity cost (€/kW h), E_{cons} is the electricity consumption (kW h/km) and C_{mc} is the maintenance costs. The yearly operating distance in a route is calculated as

$$D_a = v_{avg}T_{op} \tag{12}$$

where v_{avg} is the cycle specific average driving speed and T_{op} is the operation time in a year.

6.2. Cost calculation parameters

Table 7 presents the parameters for the cost-benefit analysis. The capital cost (C_{cap}) of the conventional diesel bus corresponds to purchase costs of a Euro 6 emission level diesel bus in Europe (Lastauto Omnibus, 2013). This cost is also used as the reference value for calculating the capital cost of the other bus configurations. Based on the cost estimations presented in literature (Table 1), the capital costs of the hybrid and electric buses were defined in relation to the costs of a Euro 6 diesel city bus. The capital costs were assumed to be

- 40% ($f_C = 1.4$) higher for the parallel hybrid with ultracapacitors (PAR_1),
- 50% ($f_C = 1.5$) higher for the parallel and series hybrid with a battery (PAR_2 and SER_1),
- 60% ($f_C = 1.6$) higher for the plug-in hybrid bus (SER_2), and
- 100% ($f_C = 2.0$) higher for the electric bus (EV).

Table 7
Parameters for the cost-benefit analysis.

Parameter	abbr	Value
Diesel city bus capital cost (€)	C_{cap}	225,000
Diesel fuel cost, EU average 12/2012 without VAT (€/l)	C_{fuel}	1.185
Electricity cost without VAT (€/kW h)	C_{elec}	0.10
Maintenance cost for diesel bus (€/km)	C_{mc}	0.14
High power battery cost (€/kW h)	C_{batt_hp}	1000
High energy battery cost (€/kW h)	C_{batt_he}	750
Ultracapacitor system cost (€)	C_{ucap}	15,000
External charging equipment cost (€)	C_{chg}	200,000
External charging power for electric bus (kW)	P_{chg}	100
Operation time in a year (h)	T_{op}	4000
Service life in years	T_s	12
Discount rate (%)	d_{rate}	7

The maintenance costs (C_{mc}) were same for all the bus configurations. As there is less frequent need for maintenance of the electric powertrain, and with electric bus there is no engine to be maintained, slightly lower maintenance costs could be justifiable for hybrid and electric buses. Moreover, it was observed by Barnitt (2008) that the operating costs of hybrid buses were reduced by the new generation of hybrid buses. Currently commercially available lithium based batteries are used as a reference but also predictions of future costs are taken into account in the sensitivity analysis. The battery second life costs or opportunities are not considered in this research. The external charging equipment costs are only taken into account for the plug-in hybrid and electric city bus.

Because the driven distance between the operation routes is largely different, the operation hours (T_{op}) were used as a reference for yearly operation in the life cycle cost calculation. The average service life of a city bus varies typically between 10 and 15 years (Nylund and Koponen, 2012; Clark et al., 2008; Laver et al., 2007).

7. Results and discussion

7.1. Energy consumption and emissions

The simulation results clearly show that the energy efficiency of the city bus can be significantly improved by hybridization and electrification. This improvement depends strongly on the degree of electrification thus how much electrical energy can be used for the operation. The energy efficiency has quite large variation depending on the driving cycle and bus configuration. Fig. 3 presents a summary of the energy consumption variation for each bus configuration. These results show that the plug-in hybrid and electric city bus have much lower energy consumption than the other bus configurations, and also the driving cycle has less influence on their energy consumption. Similar energy consumption values have been presented in recent literature e.g. (Suh et al., 2012; Muncrief et al., 2012). These results also match to recently measured fuel consumption from existing diesel and hybrid buses (Nylund and Koponen, 2012) in which the average consumption in Braunschweig cycle was 4.3 kW h/km for EEV (Enhanced Environmentally friendly Vehicle) type diesel bus, 3.2 kW h/km for parallel hybrid bus, and 3.0 kW h/km for series hybrid bus. However, there are no available, comparable results of the energy consumption in the literature for the plug-in hybrid and electric city buses because their commercialization is in early stages.

In Fig. 4 the reduction of the regulated emissions – hydrocarbon (HC), carbon monoxide (CO), nitrogen oxides (NOx) and particulate matter (PM) – are presented for the hybrid city buses. The impact of the driving cycles is much higher on the emissions than on the energy consumption, especially with battery powered charge-sustaining parallel and series hybrid buses (PAR_2 and SER_1). The plug-in hybrid (SER_2) has a lot of potential to reduce emissions despite of the driving cycle due to the large portion of pure electric operation. It should be noted here that no measures for optimizing the engine operation in terms of emissions were carried out therefore the reductions of the emissions could actually be higher than these results indicate. The emissions are calculated on the basis of grams per kilometer.

The impact of the driving cycle is presented in Fig. 5 where the energy consumption is showed as function of the average driving speed in operation. The average driving speed has no significant impact on the plug-in hybrid and electric city bus energy consumption. The low speed operation (<15 km/h) increases heavily the energy consumption of the engine operation dominated bus configurations. Low average driving speeds and high number of stops per driven distance also increases the percentage of the energy consumption by auxiliary devices when operating mostly on electric mode (SER_2 and EV). This can be seen in Fig. 6 which also underlines the fact that higher the portion of the electric operation is, the higher is the portion of the auxiliary energy from the total energy consumption. This could be challenging in severe climate conditions where either powerful air conditioning or heating is required for passenger comfort. Compared to the conventional diesel bus, the average energy consumption of the auxiliary devices was about the same for PAR_1, 20–30% less for the battery hybrid buses (PAR_2, SER_1 and SER_2), and almost 50% lower for the electric bus.

The energy storage system (ESS) has an important role both in the energy efficiency and the overall cost-efficiency of the city bus. This role can be illustrated by the specific metric called energy throughput per kilometer (kW h/km) which also

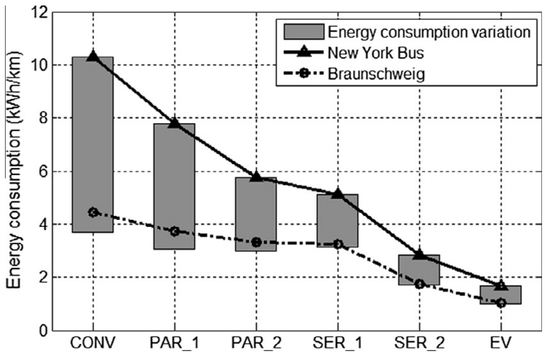

Fig. 3. Variation of the energy consumption.

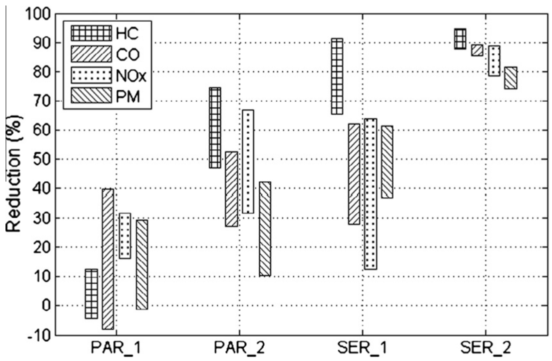

Fig. 4. The reduction of the regulated emissions for hybrid city buses.

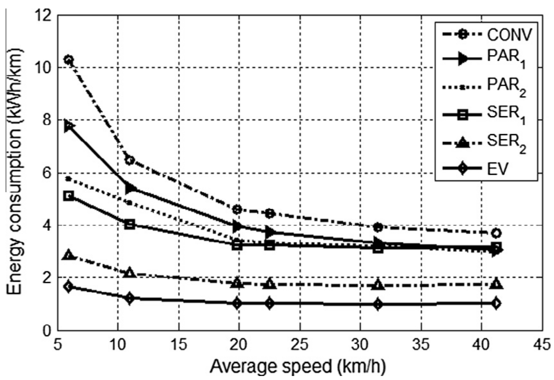

Fig. 5. The energy consumption as function of the average driving speed.

serves for the battery life estimations. Fig. 7 shows the total energy consumption as function of the energy throughput of the energy storage system for each bus configuration and operation route (the markers correspond to the routes).

The results of the conventional bus are presented here only for illustrating the differences between the bus configurations. These results actually explain the effect of the degree of electrification on the energy consumption. With low level of electrification (PAR_1 and PAR_2), the energy throughput remains 2–3 times less than with full electrification (EV), and the energy consumption variation is quite high. A hybrid with a higher degree of electrification (SER_1 and SER_2) has as high energy throughput of the energy storage as the full electrification but the total energy consumption is still higher.

7.2. Cost-benefit analysis results

The required number of buses for fleet operation was calculated as presented in section 4. Table 8 presents the size of the bus fleet for each bus configuration and operation route. The cost efficiency for the different bus configurations was evalu-

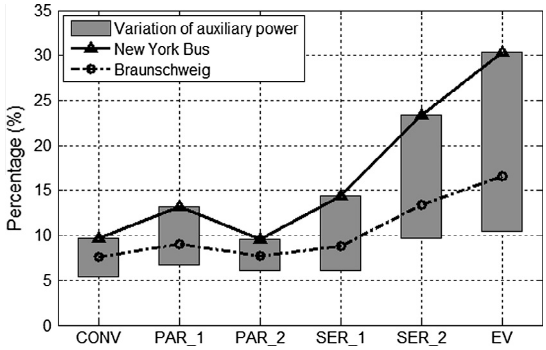

Fig. 6. The auxiliary energy consumption as percentage of the total energy consumption.

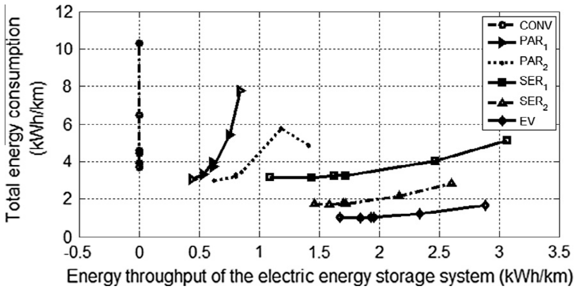

Fig. 7. Total energy consumption in function of the energy throughput of the energy storage system.

Table 8
Number of buses in fleets for the different operation routes.

Configuration	550	BR	H3	MAN	NYC	OCC
CONV, PAR and SER	6	6	4	11	12	5
EV	8	7	5	12	13	6

ated from various points of views. Fig. 8 presents the life cycle cost breakdown of the different bus fleets in all operation routes. The parameters used in this calculation were presented in Table 7. With these parameters, hybrid buses have almost the same life cycle cost than the diesel city bus. There are no significant differences between the charge-sustaining parallel and series hybrid buses (PAR_1, PAR_2 and SER_1). The series hybrid performs better in the operation where the average speed is low (Manhattan and New York Bus) and the parallel hybrid has better performance in the higher average speed operation (550 and Helsinki3). Due to the high capital cost and expensive battery replacements of the electric city bus, it is the most expensive choice in all the routes. The impact of the operation schedule can be seen between the routes Braunschweig and OCC. These routes have similar characteristics but the operation interval for Braunschweig is higher which changes the cost efficiency when comparing the different bus configurations to each other.

Fig. 9 presents the required capital cost factor of individual bus for breakeven of the life cycle costs when the service life is 12 years. The variation in the cost factor comes from the impact of the operation route. These results show that with the chosen capital costs (corresponding reference cost factors 1.4, 1.5, 1.5, 1.6 and 2.0), the life cycle costs of the hybrid and electric buses are not lower than the conventional diesel except the PAR1 in the operation route H3. However, the results show that if the capital costs of hybrid buses are 40% higher than conventional diesel bus, the hybrid buses could have lower life cycle costs in certain operation routes. The variation is very large for the electric bus meaning that it should be carefully evaluated in which kind of operation electric buses are used.

Fig. 10 shows the variation of the life cycle operation costs over the service life of a bus. The driving cycles have less impact on the operation costs of the hybrid and electric buses. When comparing these results to life cycle operating costs presented in recent studies, there are no significant differences e.g. in (Croft McKenzie and Durango-Cohen, 2012), the life cycle operating costs for conventional diesel bus was 0.82 €/km, and for diesel hybrid bus 0.75 €/km. The replacement costs for the energy storage system play an important role for plug-in hybrid and electric bus as these costs are about 25% of the total operating costs for the plug-in hybrid and more than 50% for the electric bus.

Fig. 11 presents the sensitivity of the life cycle costs by showing the effect of certain key parameters on the life cycle costs. The effect of each parameter is calculated individually in relation to the reference case. According to these results, the lower

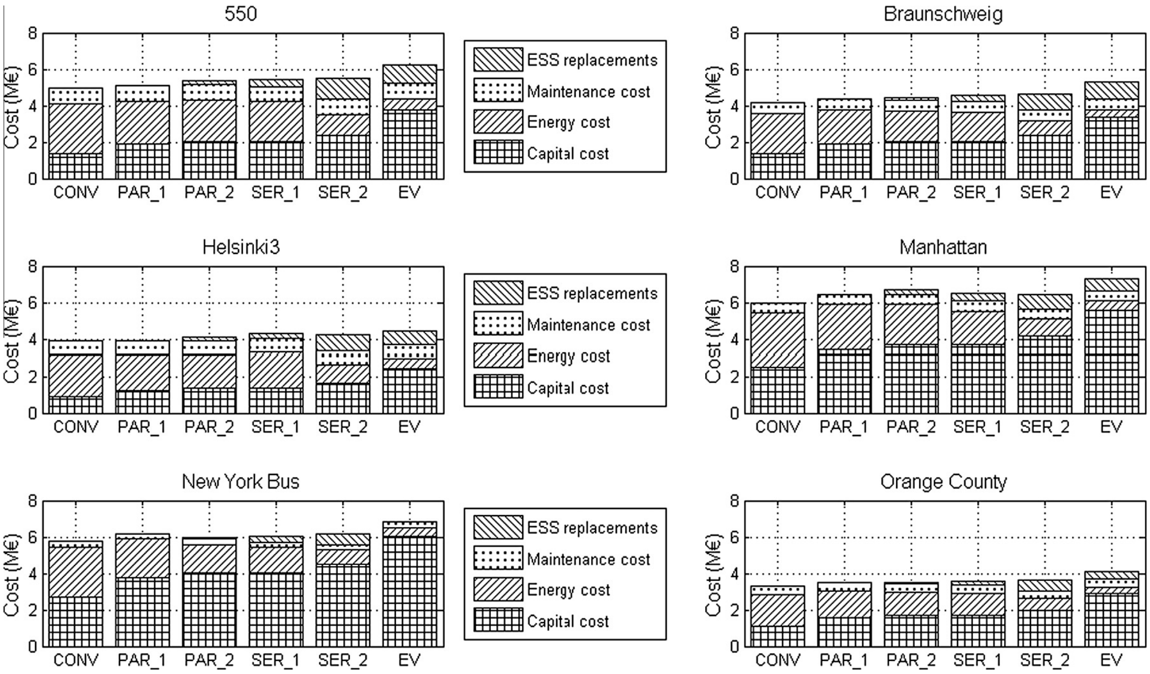

Fig. 8. Life cycle cost breakdown in different operation routes.

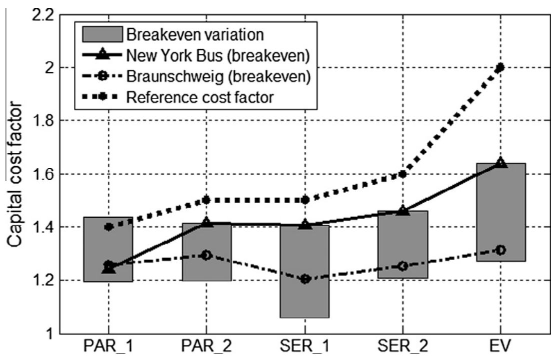

Fig. 9. Variation of capital cost factor for breakeven in life cycle costs.

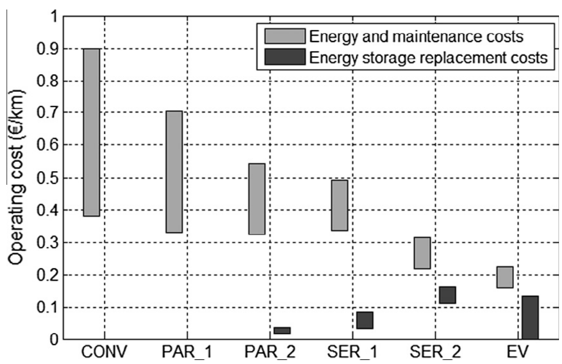

Fig. 10. Variation of the life cycle operating costs.

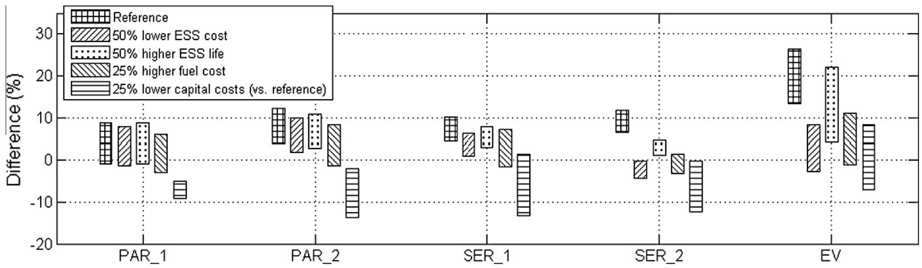

Fig. 11. Life cycle cost sensitivity to various parameters.

cost and longer life for the energy storage system does not have a significant impact on the life cycle costs of the charge-sustaining parallel and series hybrid bus (PAR_1, PAR2 and SER_1) whereas the energy storage system costs have notable impact on the plug-in hybrid and electric bus life cycle costs. 25% Higher fuel costs reduce the life cycle costs of the configuration SER_2 and EV around 10%. The 25% reduction to the capital cost (cost factors 1.05, 1.125, 1.125, 1.2, 1.5) reduces significantly the life cycle costs of each bus configuration and would make them more profitable in terms of life cycle cost than the conventional diesel bus. Based on these results, it can be concluded that the most efficient way to increase the cost efficiency of the hybrid and electric city buses is to reduce capital and energy storage system costs. However, it should be kept in mind that as the cost-benefit analysis shows, the variation of the life cycle cost is large between the different operation routes. This underlines the importance of choosing the alternative technology on the basis of the operation.

8. Conclusions

There are several factors which contribute to the cost efficiency of city buses. According to the results acquired by a thorough energy consumption and cost-benefit analysis in fleet operation, it can be concluded that the capital and energy storage system costs are the most critical factors for hybrid and electric city buses. Even though hybrid and electric powertrain technology can clearly improve the energy efficiency, the benefit it contributes in the cost efficiency depends also on the operation route and schedule. The plug-in hybrid and electric city buses seem to have the best potential because they are less impacted by the driving cycle, and the energy storage system cost is large part of their life cycle costs. It is estimated in many occasions that the costs for the batteries will decrease in the future, which gives strong reason to believe that these two bus configurations have tremendous potential to lower the life cycle costs, and improve significantly energy efficiency as well as reduce the emissions. In fact, there seems to be much more potential to reduce the emissions than the energy consumption. However, the emission reduction may not provide any advantages/benefits in terms of life cycle costs without any financial incentives or supporting legislation such as requirements of pollution free zones.

Based on the results of this research, certain recommendations for transit agencies can be drawn concerning to the selection of alternative powertrain technologies for city buses. First, it is highly important to take into account the operating environment and understand the technical performance of the new technologies in different conditions. Secondly, the advantages of the alternative powertrain technologies in terms of energy efficiency, and especially in the competition against traditional diesel buses should be thoroughly investigated for the service life of the buses. In the management of the life cycle cost of a city bus fleet, many factors have to be considered and with hybrid and electric buses a special attention should be given for the operation route scheduling and planning. In this perspective, more research should be done for understanding in detail the dependence of the life cycle cost on the component dimensioning (especially battery) and operation scheduling especially in the case of plug-in hybrid and electric city buses.

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