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

Antti Lajunen *

Aalto University, School of Engineering, Puumiehenkuja 5a, 02150 Espoo, Finland

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A B S T R A C T

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.

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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

* Tel.: +358 40 525 8164; fax: +358 9 470 23469.
E-mail address: antti.lajunen@aalto.fi

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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).

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