Energy 106 (2016) 329–342

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Lifecycle cost assessment and carbon dioxide emissions of diesel, natural gas, hybrid electric, fuel cell hybrid and electric transit buses

Antti Lajunen [a, b, *], Timothy Lipman [a]

[a] Transportation Sustainability Research Center, University of California at Berkeley, 2150 Allston Way, Suite 280, CA 95704, USA
[b] Aalto University, School of Engineering, Puumiehenkuja 5a, 02150 Espoo, Finland

ARTICLE INFO

Article history:
Received 23 July 2015
Received in revised form
9 February 2016
Accepted 16 March 2016
Available online 6 April 2016

Keywords:
Lifecycle costs
Carbon dioxide emissions
City bus
Hybrid
Fuel cell
Battery

ABSTRACT

This paper evaluates the lifecycle costs and carbon dioxide emissions of different types of city buses. The simulation models of the different powertrains were developed in the Autonomie vehicle simulation software. The carbon dioxide emissions were calculated both for the bus operation and for the fuel and energy pathways from well to tank. Two different operating environment case scenarios were used for the primary energy sources, which were Finland and California (USA). The fuel and energy pathways were selected appropriately in relation to the operating environment. The lifecycle costs take into account the purchase, operating, maintenance, and possible carbon emission costs. Based on the simulation results, the energy efficiency of city buses can be significantly improved by the alternative powertrain technologies. Hybrid buses have moderately lower carbon dioxide emissions during the service life than diesel buses whereas fully-electric buses have potential to significantly reduce carbon dioxide emissions, by up to 75%. The lifecycle cost analysis indicates that diesel hybrid buses are already competitive with diesel and natural gas buses. The high costs of fuel cell and battery systems are the major challenges for the fuel cell hybrid buses in order to reduce lifecycle costs to more competitive levels.

1. Introduction

The rapid technological development of electric powertrains in recent years has greatly increased interest in alternative powertrain technologies in city buses. An extensive lifecycle cost analysis indicates that hybrid electric buses are already economically competitive with diesel buses, and electric buses would be cost effective in the near future [1]. GHG (Greenhouse gas) emissions of different city bus technologies have also been the subject of recent analysis [2]. The results have shown that hybrid and electric buses has a significant potential to reduce CO_2 (carbon dioxide) and other GHG emissions. Croft McKenzie and Durango-Cohen [3] concluded that the alternative fuel buses reduce operating costs and emissions, but increase life-cycle costs. Hybrid electric city buses are becoming more popular all around the world but despite their technological maturity, these buses have not been able to replace the conventional diesel buses in a large scale. The fuel economy of diesel buses has not significantly improved during the last decade, and the stricter emission regulations lay out more challenges that can even increase the fuel consumption and maintenance needs [4]. Natural gas buses actually have higher energy consumption than diesel buses but their pollutant emissions are lower, which makes them interesting in city center operations [5]. The CO_2 emissions of natural gas buses were found to be lower than for diesel buses in one recent study [6] but a study of buses in Beijing, China [5] shows about the same amount of CO_2 emissions for natural gas and diesel buses.

As an emerging option, there have been several hydrogen fuel cell bus demonstration trials around the world, and there are increasing amount of fuel cell buses in service operation e.g. BC Transit (British Columbia Transit) [7], AC (Alameda-Contra Costa) Transit in Berkeley/Oakland [8], and CUTE (Clean Urban Transport for Europe) [9]. The underlying PEM (proton-exchange membrane) fuel cell technology is approaching the market maturity phase but the costs are still high. According to a recent review article [10], the main barriers for fuel cell buses are lack of infrastructure for refueling, the high bus capital costs, and fuel costs. A European study [11], estimates that fuel cell buses will have diesel bus cost levels by 2025–2030. The continued development of fuel cell bus technology is often justified due to their environmental benefits over other bus

* Corresponding author. Aalto University, School of Engineering, Puumiehenkuja 5a, 02150 Espoo, Finland. Tel.: +358 40 525 8164.
E-mail address: antti.lajunen@aalto.fi (A. Lajunen).

http://dx.doi.org/10.1016/j.energy.2016.03.075
0360-5442/

technologies [12], combined with favorable operational characteristics compared with battery electric buses.

Fuel cell buses and battery electric buses have the advantage of not producing any pollutant emissions directly from their operation. Their emissions are entirely “upstream” related to fuel production of electricity and hydrogen and no tailpipe emissions are released. This is especially advantageous in city centers where there is typically heavy traffic and air quality can be poor. Battery electric buses are also interesting because their energy consumption is very low when idling comparing to conventional diesel buses. The powertrain of electric city buses can have different layouts but it usually has a minor impact on energy consumption [13]. The electric buses in demonstration operations in Seoul [14] and Los Angeles [15] are typical modern electric buses with lithium-ion batteries as energy storage. The main challenges with electric buses are the relatively expensive battery system and charging infrastructure [16,17]. Lithium-based batteries offer good performance and energy density, but their costs are still quite high (even with cost declines in recent years) and their operational lives can be short in energy intensive operation, such as for city buses. Bus battery warranties for buses employing lithium-based batteries are typically about 5–6 years, compared with 12 + year operational lives of typical urban buses [18]. In cold operating conditions, significant amount of energy is needed for the heating of the interior space, which reduces the operating range of battery electric buses. This underlines the importance of efficient thermal management in electric powertrains [19]. Recently, advanced methods have been proposed for the thermal management challenges of electric vehicles e.g. active cooling/heating for batteries [20] and using a small fuel cell stack as heat producer [21]. Fuel cell buses are also costly at present, and they suffer from the difficulty of installing and operating the necessary hydrogen fueling infrastructure. However, with steady progress and projected cost decreases in fuel cell and hydrogen storage technology, fuel cell hybrid buses are getting more cost effective every year [22,23]. The barriers of fuel cells were extensively analyzed in a recent study [24] where focus was to understand the challenges occurring when scaling up from cell to stack level.

The lifecycle costs of different types of passenger vehicles have been widely analyzed in the literature (e.g., see Refs. [25–29]). In the case of city buses, however, much less scientific research has been done. Only a few comprehensive research studies have evaluated the lifecycle costs of different types of powertrain technologies in city buses, e.g. Refs. [1] and [3]. A more recent focus has been LCA (life-cycle assessment) of the energy and CO_2 emissions of alternative bus powertrains. LCA of different fuel chains and powertrains for city buses were evaluated in Ref. [30]. The research results for a setting in Kaunas, Lithuania indicate that biogas-powered buses and electric trolleybuses are best alternatives to modernize public transport fleet. A Chinese study [31] recommends application of hybrid technology to diesel buses, efforts to commercialize electric buses, and support of fuel cell buses and hydrogen technology for future potential applications. Electric buses are also emphasized in a very recent research study in which CO_2 and pollutant emissions were calculated for different bus technologies [32]. The study also underlined the geographic influences in terms of fuel pathways and operating conditions on the total CO_2 emissions of the buses. Another recent study suggests that natural gas buses have the lowest impact on public health costs and that battery electric buses have the highest lifecycle costs of the options studied [33]. However, these types of studies do not usually consider the cost information that is needed to have a broad understanding of the cost effectiveness of the alternative powertrain technologies in relation to energy use and CO_2 emissions.

This research focuses on the evaluation of the lifecycle costs of different types of city buses. In this research diesel, natural gas, hybrid electric, fuel cell hybrid and battery electric city buses are considered. The energy consumption of the different buses is defined with vehicle simulation by using the Autonomie vehicle simulation software, which offers a proven simulation environment for heavy vehicle evaluations [34]. All the buses were simulated in various types of operating cycles in order to analyze the differences of the powertrain technologies in different operation. The lifecycle costs are calculated for different operating scenarios of the city buses. The CO_2 emissions are taken into account from the bus operation and also from the primary energy production. The latter is done by using two different locations: Finland and California (USA). The energy production CO_2 emissions are defined by the chosen fuel production chains and are estimated using recent LCA models and literature.

In the sections below the paper first presents key challenges with the implementation of alternative powertrains. Second, vehicle models and designs are presented with relevant technical specifications. Then, the lifecycle cost calculation method used in this analysis is thoroughly explained with cost data and assumptions. The selected energy pathways are then described for their “well-to-tank” (energy pathway from the original source to the fuel tank or energy storage of the vehicle) characteristics with the related carbon dioxide emissions and energy conversion factors. Finally, the simulation results are presented with detailed explanations and discussion.

2. Challenges with alternative powertrains

2.1. Battery charging

Battery electric city buses have been developed rapidly in recent years [14,15]. There are several different manufacturers with products in the market, and also the big bus manufacturers have shown interest in developing them. There are several different operating methods for electric buses due to the different options in charging methods [16]. The battery can be charged overnight at the depot, it can be charged during operation at the end stations, or during the route in dedicated bus stops. Also battery swapping has also been considered but this requires a substantial investment in a battery swapping station. Fig. 1 presents two electric bus designs for China and the USA. The Chinese BYD bus has a large battery pack with enough energy for an entire day of an airport shuttle bus operation. The Proterra electric bus has a smaller power type battery but that can be fast charged during service operation.

Recent technological developments with lithium-based batteries and associated “battery management systems” has made them the best choice as the energy storage for electric city buses [35]. The high energy type lithium-based batteries have relatively good specific energy (energy capacity to weight ratio), which can enable a full day of operation without recharging the battery during the day for some bus duty cycles. However, the required amount of battery energy to achieve this is high, which increases the bus total weight and cost. As an alternative to large high energy battery packs, high power type batteries have good power to weight ratio, and thus good specific power. These types of batteries are used with a fast charging method to charge the batteries, where the total energy carried is lower but is recharged during the day. Batteries with high charge-rate acceptance are particularly needed for opportunity charging in which very high power levels are used for rapidly charging the battery in about 30 s at a bus stop [36]. Because of the high power levels, opportunity charging can benefit from an energy buffer such as a stationary battery at the charging station to avoid large stresses to the power grid.